DESIGN AND SIMULATION
OF AUTOMATIC TAPE WINDING SYSTEM

A Thesis presented to the Faculty of the Graduate School

University of Missouri-Columbia

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

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DECEMBER 2018

The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

DESIGN AND SIMULATION
OF AUTOMATIC TAPE WINDING SYSTEM

Presented by Teng Teng

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

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ACKNOWLEDGEMENTS

This research effort wound not have been possible without the extensive help and guidance from my faculty advisor, Dr. Thomas G. Engel. His knowledge was invaluable when finding solutions to the many stumbling blocks encountered during this research effort. He was always available, and his door and ears were always open.

I would also like to thank my project partner Xuehui Zhu, who provided many useful methods, gave some wise suggestion to this research all the time.

TABLE OF CONTENTS

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ABSTRACT

Based on two-axis manual tape winding machine, this paper describes and developes 3-axis automatic tape winding system. Beginning with motor analysis, discussion on the relationship between motors torque, angular velocity and winder inertia, calculation of required torque and tape tension, and connecting hardware parameters with estimated physical environment. The second part provides two methods for tension measurement and two methods of tension control, comparing their differences and errors. Then associates with previous calculations, we converted the hardware parts into mathematical model in MATLAB/ Simulink, separated the whole system into control module with PID control algorithm, motor drive and spindle model module. The simulation of the closed-loop tension control winding system is finally realized.

CHAPTER 1 INTRODUCTION

A winding machine or winder is a machine for wrapping string, twine, cord, thread, yarn, rope, wire, ribbon, tape, etc. onto a spool, bobbin, reel, etc. [1] It is widely used in fabric manufacturing. Winding as one of the most important operation which is more than just transferring material from one package to another, further functions of winding are to inspect and to eliminate any faults on the material to ensure the quality of the material.

Mechanized winders have a center core (a bobbin, spool, reel, belt-winding shell, etc.) on which the material is wound up. [1] In the case of a tape winding machine, which works similar to a filament winding machine, tape winding is a process for placing a series of continuous adhesive tapes including PE, PET, masking paper tapes, double sided tapes, electrical tapes on a rotating spindle surface in a specified geometric pattern to achieve specific mechanical properties.

The center roll or spindle is often driven by a high-powered motor to wind and shape tapes on the roll according to their intended purpose. The spindle will have greater angular velocity

Figure 1-1. Two-axis manual tape winding machine

when it runs at a small torque, on the contrary, it will have a low speed when motor provides high potential torque. Edge sensors are used to sense how full the center roll is by continuously measuring its diameter. They are mounted on adjustable slides to accommodate many different widths which increase as the center roll is filled.

In this project, we focus on a tape winding machine based on an original one in the lab shown in figure 1-1. This is a manual tape winding machine where we always need to control the length and thickness of the rewind to make sure the tape is not over wound or broken. Therefore, the goal of this research is to better control the two-axis manual tape winding machine, design a 3-axis closed-loop automatic control winding system, and simulate the entire process.

CHAPTER 2 MOTORS

The whole process of winding can be separated into rewind (spindle), tension roller and unwind (carriage) three parts. There are three motors required to drive these three parts in different axis to implement the basic winding function on the tape winding machine. The Three motors are listed below, and for each of these motors, we will discuss their working principles.

The spindle motor, which supplies power to the shaft and drives spindle to rotate. After the tape is stuck on the winding roll, the shaft spins the roll then the tape starts to be wound on the spindle.

The tension wheel motor, which will connect to a tension sensor directly, is used to measure the tension on the tape then the signal will be sent to the controller to compare with a setting point, after that a control signal from the controller to the spindle motor to adjust the speed of spindle motor and then adjust the tension on the tape. The tension motor drives the tension wheel provides appropriate resistance on the tape to make sure it will be tightly wrapped on the roll.

The carriage motor, the role of carriage motor is to drive the transmission track which can convey the unwind moving within a limited length, then the tape will be evenly wound around the spindle to ensure it is fully wound.

2.1 Spindle Motor

The purpose of spindle motor is to run the spindle at a certain speed and can quickly adjust spindle angular running speed once received signals.

2.1.1 Work Process

The work block diagram shown in figure 2-1 illustrates the work process of the rewind module. It changes the output torque by receiving the signals from the current spindle radius and tension difference.

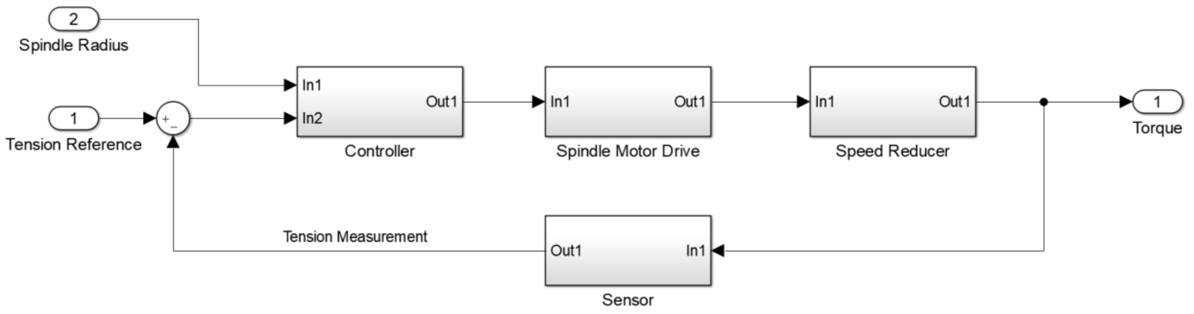

Figure 2-1. Block diagram of spindle module.

Also, given a certain tape pulling speed v_{tp} (m/s), the angular speed of the spindle changes all the time when spindle radius increases since more and more tape is wound on it. The relation between the spindle radius R_{sp} (m) and its angular velocity ω_{sp} (rpm) is shown in equation 2.1.

$$\omega_{sp} = \frac{30}{\pi} \cdot \frac{v_{tp}}{R_{sp}} \tag{2.1}$$

2.1.2 Motor Selection

To select a proper motor, we start with estimating the required torque on the spindle. Inertia of the spindle model is shown in figure 2-2, and it can be calculated by the equation 2.2.

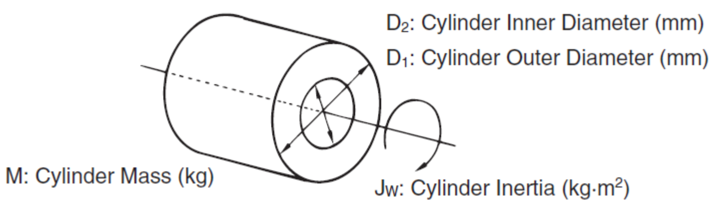

Figure 2-2. Inertia of circular cylinder

$$J_{sp} = \frac{1}{8}\, M\, (D_1^2 + D_2^2) \tag{2.2}$$

Where J_{sp} is the spindle inertia, we assume that the spindle radius starts at 5cm ($D_2 = 0.1\, m$) and will be fully filled at 21 cm ($D_2 = 0.42\, m$). Considering the mass of the spindle increase depends on its radius, we set its maximum mass as 40 kg (M = 40 kg), therefore the maximum spindle inertia:

$$J_{spmax} = 0.932\, kg \cdot m^2$$

Assuming the angular velocity of the spindle will not run more than 60 rpm ($\omega_{sp} < 6.3\, rad/s$), the full speed can be achieved in 0.2s then the acceleration of the spindle will be $\alpha_{sp} = \frac{6.3}{0.2} = 31.5\, rad/s^2$. The required torque of the spindle is as follows:

$$\tau_{sp} = J_{sp} \cdot \alpha_{sp} \approx 30\ \mathrm{N \cdot m}.$$

Based on a $30\ \mathrm{N \cdot m}$ torque output requirement, we considered using a stepper motor with a gearbox it is capable to supply high torque at low speeds. The torque-speed curve of the motor we selected is shown in figure 2-3, it satisfies our estimated requirement.

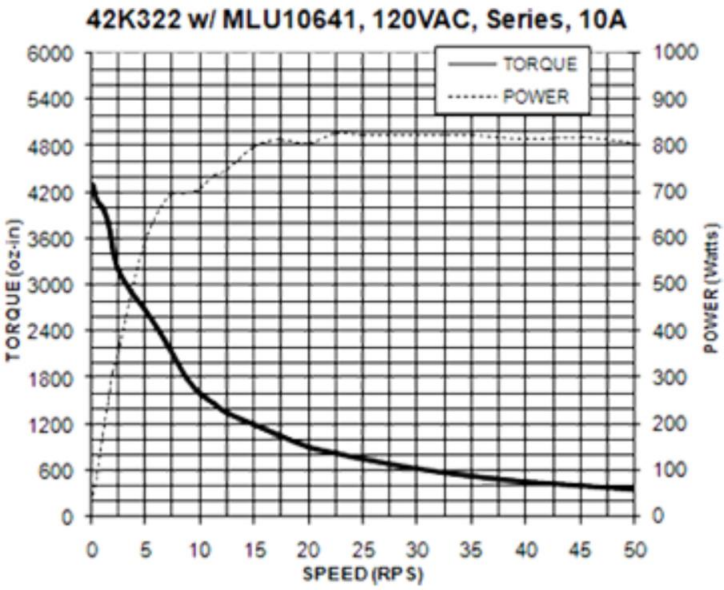

Figure 2-3. Torque- speed curve of spindle motor.

The output torque and speed of the spindle can be calculated by equations 2.3 and 2.4, η represents the efficiency of the gearbox and typically reaches 1.

$$\tau_{sp} = \eta n_1 \tau_{in} \tag{2.3}$$

$$\omega_{sp} = \frac{\omega_{in}}{n_1} \tag{2.4}$$

The relation is shown in figure 2-4 after the spindle motor equipped with a gearbox (gear ratio $n_1 = 15$).

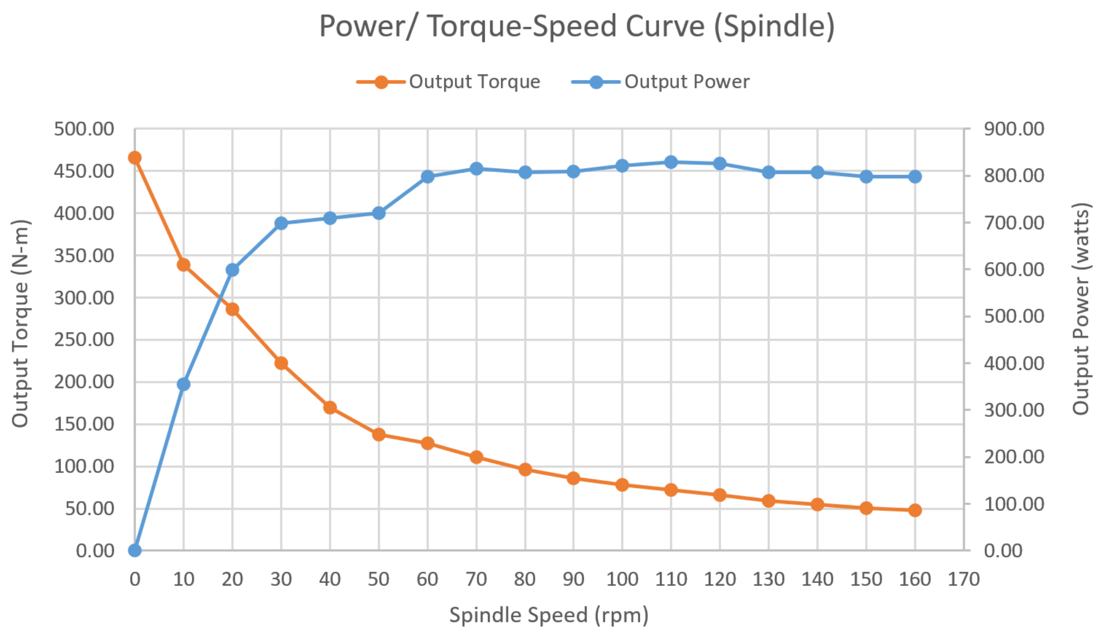

Figure 2-4. Power/ torque-speed curve of spindle ($n_1 = 15$, $\eta = 1$).

2.2 Tension Wheel Motor

A tension wheel motor is used to drive a tension wheel directly and works together with

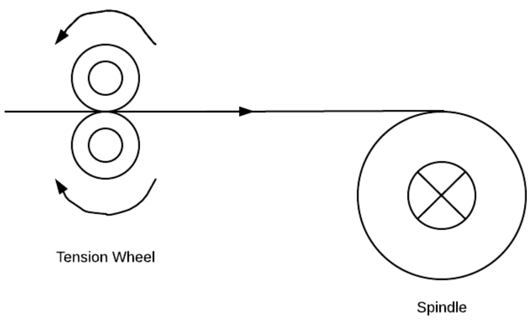

Figure 2-5. Tension wheel model

the spindle motor to keep the certain tension on the tape. The model figure, as shown in figure 2-5, is comprise of two tension wheels compressed tightly to make sure the tape will not slip easily, also, we assume that the tape is not made of elastic material. Therefore, the tape tension wheel will keep the same linear speed as the spindle wheel when there is no tension applied on the tape. Tension control and measurement methods will be discussed in chapter 3.

2.3 Carriage Motor

The function of a carriage motor is to move the carriage (unwind) module back and forth along the spindle direction. The tape from the unwind will be pulled from the spindle and wound on the spindle continuously. The running speed of the carriage motor determines the linear speed of the unwind. Based on different requirements, the spindle can be filled with tape in several different ways. Figure 2-6. and 2-7 show two cases of how the tape winds on the

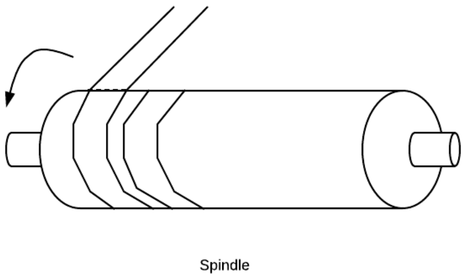

Figure 2-6. Unwind moves slow case

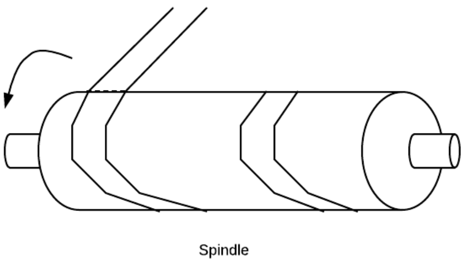

Figure 2-7. Unwind moves fast case.

spindle when unwind moves as different velocities and spindle angular velocity remain constant.

To control the speed of the unwind, we related it with spindle angular velocity and tape spacing, as shown in Figure 2-8. The unwind module linear velocity v_{ca} (m/s), tape spacing Δx (m), and spindle angular velocity ω_{sp} (rpm) satisfy the equation in 2.5.

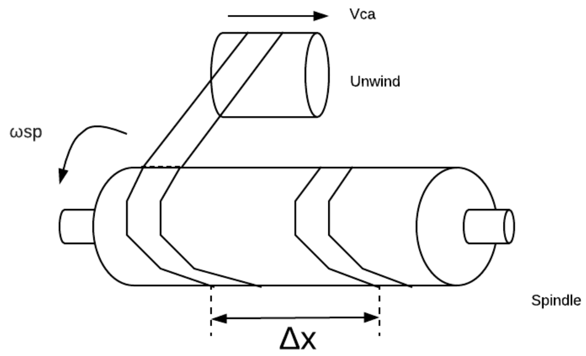

Figure 2-8. Unwind and Rewind Module.

$$v_{ca} = \frac{\Delta x \cdot \omega_{sp}}{60} \tag{2.5}$$

The way unwind module driven by motor can be categorized as rack and pinion, which is a type of linear actuator that comprises a pair of gears which convert rotational motion into linear motion, as shown in figure 2-9. The linear moving speed of rack depends on gear rotation speed that is provided by motor.

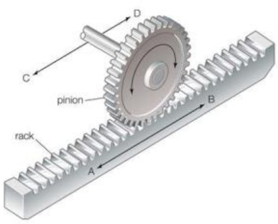

Figure 2-9. Rack and pinion diagram.

The carriage motor can be selected by analyzing the inertia of the rack and pinion. Inertia model is shown in figure 2-10.

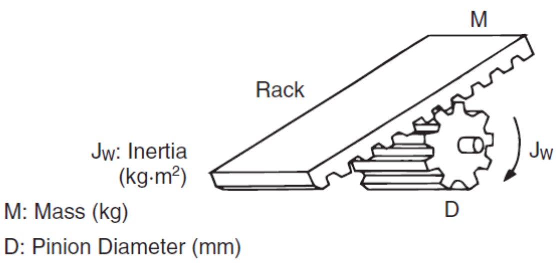

Figure 2-10. Inertia of rack and pinion.

Its inertia can be calculated by equation 2.6.

$$J_{ca} = \frac{1}{4} M{D_{ca}}^2 \tag{2.6}$$

Assume that the diameter of the gear is 0.1 m (D = 0.1 m), the mass of the load (unwind module) is 20 kilograms (M = 20 kg), therefore the carriage motor inertia is:

$$J_{ca} = 0.05\ kg \cdot m^2.$$

Assume the highest linear speed (rapid homing speed) of a load is 1m/s, then the highest angular velocity of the carriage motor is $\omega_{camax} = \frac{1}{0.05} = 20\ rad/s$, if this value can be reached in 0.5s, the motor acceleration will be $\alpha_{ca} = \frac{20}{0.5} = 40\ rad/s^2$, the required torque on the carriage motor

$$\tau_{ca} = J_{ca} \cdot \alpha_{ca} = 2\ \mathrm{N} \cdot \mathrm{m}.$$

By combining equations 2.1 and 2.5, the carriage motor with gearhead (gear ratio n_2) angular velocity can be described by equation 2.7.

$$\omega_{ca} = n_2 \cdot \frac{1}{\pi \cdot D_{ca}} \Delta x \cdot \frac{30}{\pi} \cdot \frac{v_{tp}}{R_{sp}} = \frac{30 n_2}{\pi^2} \cdot \frac{\Delta x\, v_{tp}}{D_{ca}\, R_{sp}} \tag{2.7}$$

The relationship between ω_{ca} and R_{sp} can be drawn in figure 2-11. Two curves in the chart show their relation at different tape pulling speeds.

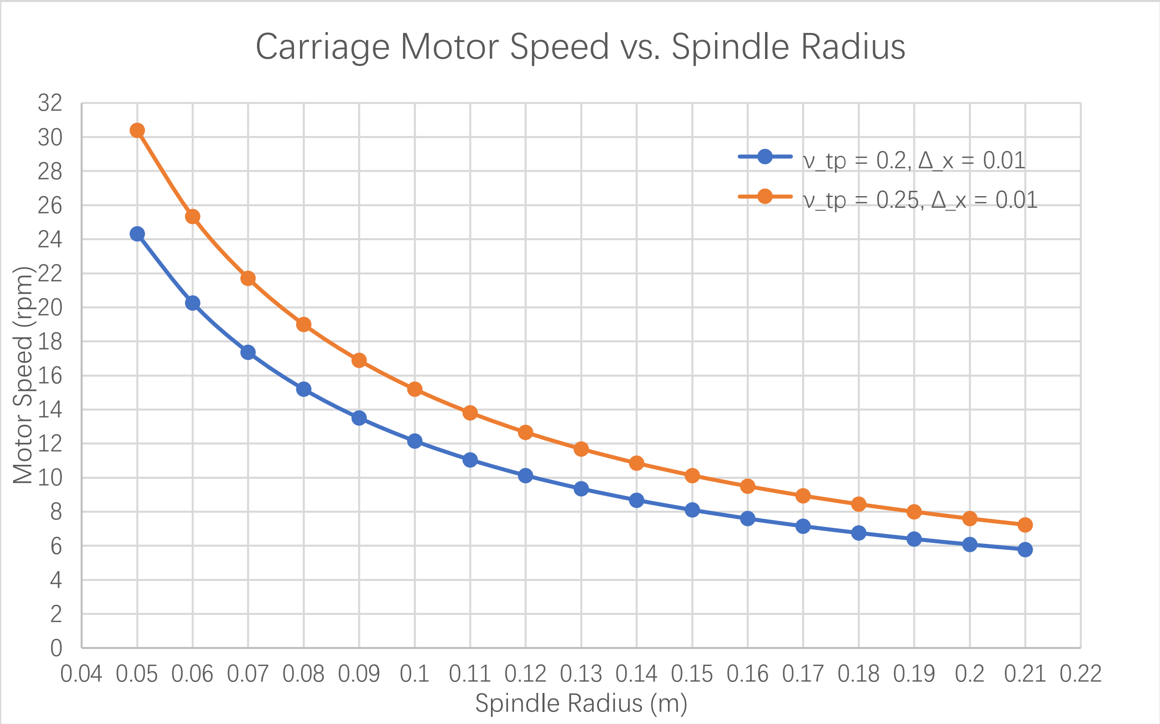

Figure 2-11. The relationship between carriage motor speed and spindle radius. ($n_2 = 20$)

CHAPTER 3 TENSION

The winding process consists of the production of mandrel and lining, the disposition of the glue solution, the filament drying, heat treatment, winding, solidification, testing, and reconditioning. [2] Among these processes, the tension control is a difficult process that has a relatively huge impact on the performance of the winding product. The constant winding tension can make the tape arranged in order and distribute the stress on tape.

3.1 Tape Tension

Properly controlled web tension results in a higher quality product and produces greater throughput. For instance, if the tension is not properly controlled, wrinkles in the material may occur resulting in defective or wasted product, (refer to figure 3-1) If a roll of material is wound without the proper tension control, the outer layers may crush the inner layers leading to starring (Refer to figure 3-2). Applying too much tension may stretch some materials beyond their elastic limit rendering them unusable. [1] Therefore, it is important to apply proper tension to a tape so that it can be handled through the machine and processed without over-stretching or wrinkling, the tape tension is critical and is necessary to be analyzed.

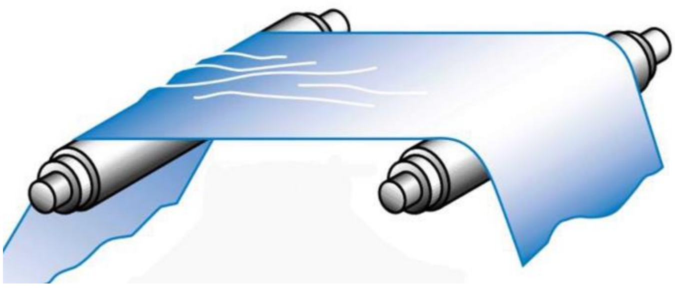

Figure 3-1. Wrinkling tape [7].

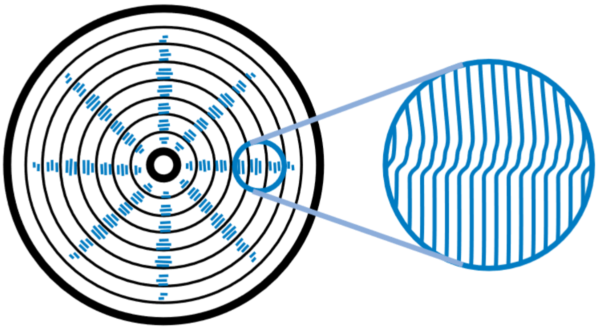

Figure 3-2. Sectional view of inner layers starring [7].

Tension is defined as the force applied to a continuous tape in the machine direction. Typically, tension is measured in pounds per linear inch (PLI) in the U.S. and is calculated by the equation in 3.1. [5]

$$\text{PLI} = \frac{\text{total pounds of tension}}{\text{tape width in inches}} \tag{3.1}$$

Then the amount of tension applied on the tape is described in equation 3.2.

$$\text{Total pounds of tension} = \text{PLI} \times \text{tape width in inches.} \tag{3.2}$$

The typical material tension conversion are shown in table 3-1.

Material	Tension (lbs./inch/mil)	Paper & Laminations	Tension PLI
Aluminum Foils	0.5 to 1.5 (1.0 average)	**20# / R - 32.54 gm/m²**	0.5 to 1.0
Cellophanes	0.5 to 1.0		
Acetate	0.5	**40# / R - 65.08 gm/m²**	1.0 to 2.0
Mylar (Polyester)	0.5 to 1.0 (.75 average)		
Polyethylene	0.25 to 0.30	**60# / R - 97.62 gm/m²**	1.5 to 3.0
Polystyrene	1.0		
Saran	0.5 to 2.0 (.10 average)	**80# / R - 130.1 gm/m²**	2.0 to 4.0
Vinyl	0.5 to 2.0 (.10 average)		

Note: 1 mil = 0.001"

Table 3-1. Tension data for typical converting materials [7].

3.2 Tension Measurement

There are various methods of measuring tension. Tension measurement includes tension transfer and tension sense, an effective measurement method will allow the system to sense and respond the tension quickly. Since the tension change on the web is tiny, it is reasonable to consider about amplify the force change. Most technologies we use today on web tension control fall into two general categories: using load cell on the tension motor wheel to response web tension change directly and connecting the pendulum dance with position sensor to reflect tension change indirectly. In this project, we will discuss the propose of the two methods of web tension measurement.

3.2.1 Load cell tension measurement

The term “load cell” is commonly used to describe scale sensors that precisely measure the force or load due to the weight of an object. The term has carried over to the web processing industry since similar sensors measure the force produced by tension in the web. [6] Load cell tension measurement is a method measuring the tension on the tape directly, as figure shown in figure 3-3,

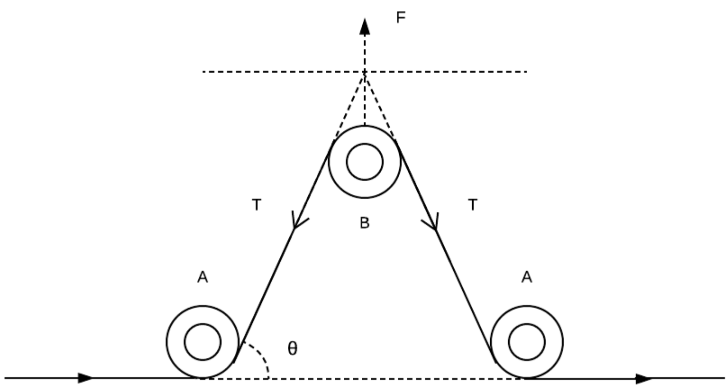

Figure 3-3. Structure of load cell tension measurement.

where it consists of two wheels A which are called guide rolls and one wheel B called cantilevered roller, tape goes beneath two guide rolls and goes above B wheel, B wheel is connected to the load cell which will reflect the force applied on it. The relationship between tape tension T and force F is given in equation 3.3. Tension on the tape will be measured and calculated by normal force on the B wheel and a feedback signal will be sent back to the controller.

$$F = 2T\sin\theta \tag{3.3}$$

From the equation 3.3 we can tell that the linear relation between normal force F and tape tension, if we assume the tape tension changes ΔT, the F will change $\Delta F = 2\Delta T\sin\theta$ correspondingly. However, if the θ is significantly smaller than 90 degrees, since the tension variety on the tape is in a small range, a slight tension change may not be easily detected by the force transducer, which could affect the accuracy of the tension control.

3.2.2 Pendulum dancer tension measurement

Pendulum dancer tension detection is an indirect force measurement method, which was selected for our project. This method is similar to position detection, which reflects the change in tape tension by detecting a change in the angle of the pendulum. Many industrial applications use dancer position feedback to indirectly regulate tension. Although widely used in the industry, pendulum dancers (the rotational motion of the dancer roller) have received very little attention in the literature compared to linear ones (translational motion). [10]

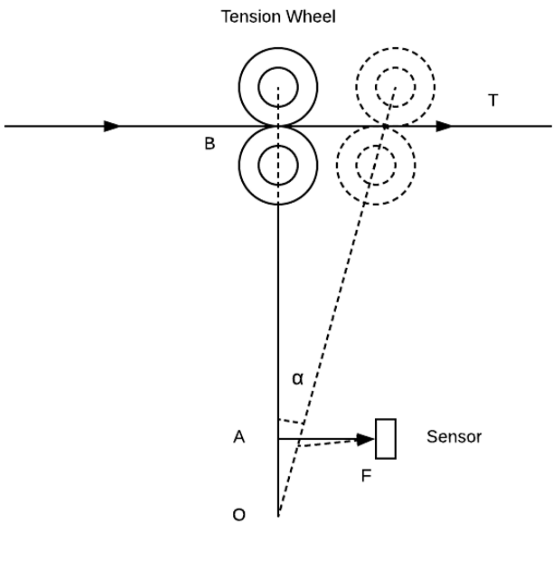

Figure 3-4. Structure of pendulum dance tension measurement.

In this paper, we introduce a new tension measurement method by using pendulum dance. The structure is shown in figure 3-4. Two tension wheels are connected to a pendulum that is long enough to reflect the angle changes, the point O is stable that allows the pendulum to swing in a small range. When the tape goes through two tension wheels, assuming there is no slip between wheels and tape, then the tape will drag the tension wheels if there is a little stretch on the tape, the tension T makes the wheels swing an angle α, at the position A near the point O, will connect to a sensor with a spring (the spring will be the natural length when the pendulum is vertical), the tension change on the tape will be expressed and amplified by an angle change on the pendulum dance which is connected to an angle position sensor. Tape tension can be expressed by equation 3.4.

$$T = k \cdot \sin\alpha \cdot \frac{l_{OA}^2}{l_{OB}} \tag{3.4}$$

Where

k: the spring stiffness coefficient;

l_{OA}: the length from point O to A;

l_{OB}: the length from point O to B.

Since angle α is very small, equation 3.4 can be simplified to equation 3.5.

$$T = k \cdot \alpha \cdot \frac{l_{OA}^2}{l_{OB}} \tag{3.5}$$

Considering that coefficient k, l_{OA} and l_{OB} are all constant, there is a linear relation between tension T and swing angle α. Variation of swing angle Δα on pendulum can be described by equation 3.6.

$$\Delta\alpha = \frac{l_{OB}}{k \cdot l_{OA}^2} \cdot \Delta T \tag{3.6}$$

When we set the ratio $\frac{l_{OB}}{l_{OA}^2}$ as a large value, a small tension fluctuation on the tape will be amplified and easily detected.

3.3 Tension control

The tension control component is important to the whole tension control system. Generally, there are three types of tension control systems: manual, open loop and closed loop. In general, closed loop tension control is the preferred method in most cases since they provide very precise and accurate tension control during steady state running conditions as well as acceleration, deceleration, and E-stop conditions. Because the material web is monitored constantly, either by load cells or from a dancer by position, changes are detected immediately, and the controlled device is changed instantaneously to maintain accurate tension control. [11] Therefore, we will focus on using a closed loop control system to achieve automatic tension control in this project.

The basic process of closed loop tension control system can be described as figure 3-5.

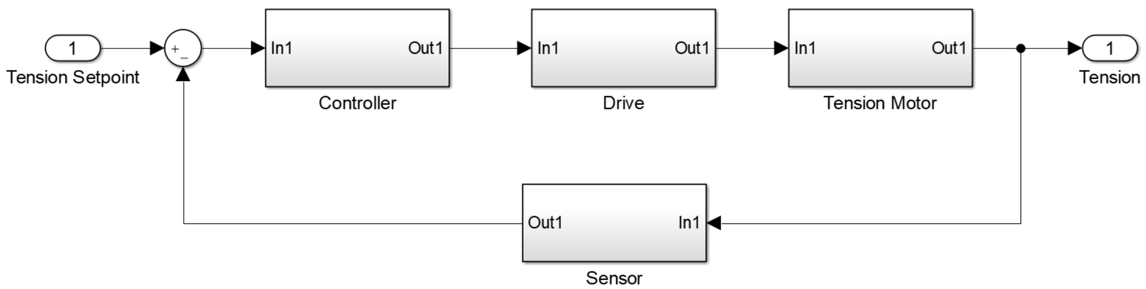

Figure 3-5. Tension control block diagram.

Once the tension value is detected by the sensor, it will be transmitted to the controller in the form of feedback and then compared with the given value of the tension. Then, according to the preset control algorithm in the controller, the control command is output to control the drive, thereby adjusting the motor speed or torque to keep the certain tension on the tape.

3.3.1 Tension Zones

A tension zone in a web processing machine is defined as the area between which the web is captured, or isolated. Virtually any machine can be broken down into tension zones, and it is important to do so to properly maintain the tension required. [5] Most winding machine applications are separated into three types of tension zones, unwind, internal and rewind. Each zone must be controlled independently. [2] However, tape tension is only desired at the rewind tension zone when it is wound and is processed, constant tape tension is essential since the tape could be either over-stretched or too loose without proper tension control. In our experiment, the tape winding machine is separated into two tension zones: unwind and rewind, as shown in figure 3-6.

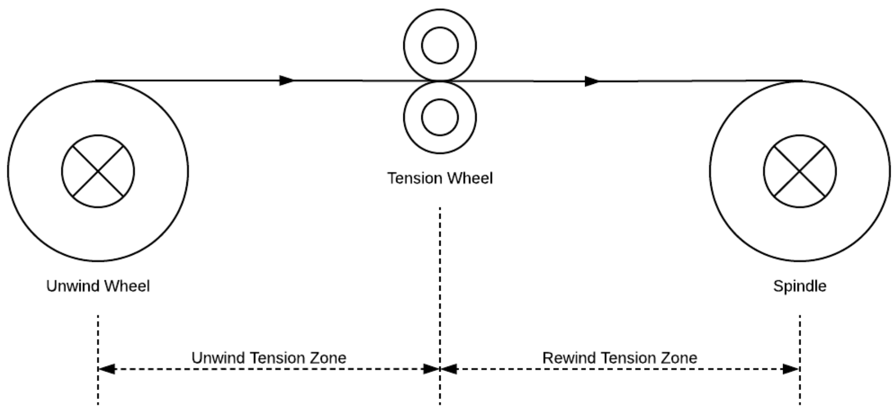

Figure 3-6. Two zones of tape winding machine (unwind and winder).

3.3.2 Tension Control Methods

Based on the rewind tension zone which includes the tension wheel and winder, we will discuss two methods to control the tension: speed control case and torque control case. We will then compare the difference and error between them. In our experiment, we assume that all the tapes we use are not stretchy material.

Speed Control

The first way to handle this problem is to control the spindle speed at the rewind station and control the tension motor wheel speed simultaneously. As shown in figure 3-7, a tiny linear speed difference between the spindle and the tension wheel will cause the tension on the tape, which makes the web become stretchy. Increasing or decreasing the speed difference between the tension wheel and spindle will change the tension on the web, thus helping change the tension by adjusting the two wheels' speed.

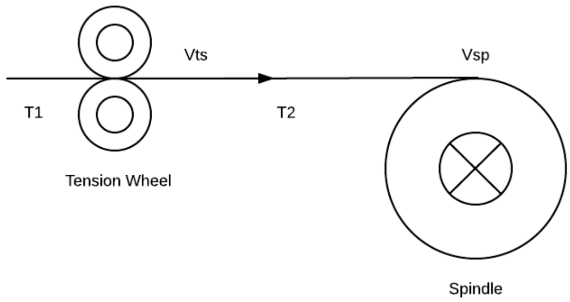

Figure 3-7. Speed control case.

Now we assume that the linear speed of spindle is υ_{sp} and the linear speed of tension wheel is υ_{ts}, the tension at the rewind zone can be described as equation 3.7.

$$T_2 = T_1 \cdot \frac{\upsilon_{sp}}{\upsilon_{ts}} + \frac{EA\,(\upsilon_{sp} - \upsilon_{ts})}{\upsilon_{ts}} \tag{3.7}$$

Where

T_1: Tension in the previous tension zone;

T_2: Rewind tension;

E: Young's modulus;

A: Cross sectional area of the material.

Now we set the $T_1 = 0$, $\upsilon_{sp} = 0.21\frac{m}{s}$, $\upsilon_{ts} = 0.20\frac{m}{s}$, $EA = 100$ N, $T_2 = 5$ N, we allow for 0.25% error in υ_{sp}, when $T_2 = 5.2625$ N, the error will be $\frac{5.2625-5}{5}$ = 5.25%. Therefore, a small error in speed control results a high error in tension. It is obvious that the error depends on the value of EA, since the tape is assumed as non-stretchy material, where the E is normally bigger than stretchy webs.

Torque Control

Torque control is a way to control the tension by changing the torque on the spindle, as shown in figure 3-8. By using a clutch or brake on the spindle motor, we can control the torque on the spindle to achieve a certain tension on the tape.

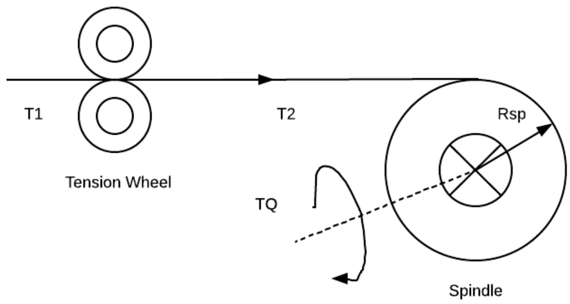

Figure 3-8. Torque control case.

As shown in equation 3.8, tension T_2 is decided by spindle torque τ_{sp} and spindle radius R_{sp}. Once we receive the feedback signal from the real tension measurement and the other feedback signal about the current spindle radius, measured by a distance sensor, we can easily increase or decrease the spindle torque to change the tension on the web after comparing the current tension with the desired tension.

$$T_2 = \frac{\tau_{sp}}{R_{sp}} \tag{3.8}$$

Where we can tell the error of tension is directly related to the torque control error, if there is 0.25% error in torque, it will only result in a 0.25% error in tension, which makes it reasonable to use this method in our project to control tension.

CHAPTER 4 SYSTEM MODEL SIMULATION

In this chapter, we will describe how we built the system model and eventually simulate the whole model on Simulink. The whole system is separated into three modules to analyze: they are spindle motor control, spindle model, and motor drive.

4.1 Spindle Motor Control Module

In our model, we assume that the final tension we required on the tape is 10 lbf (44.5 N), tape pulling speed remains at 0.2 m/s, spindle radius starts at 0.05m (unwound status) and grows linearly with 0.01m/s slope.

The control module involves the parameters we are supposed to keep their at certain values. This includes tape tension control and tape pulling speed control. Current tape running speed and measured tension will give feedback to this module in the form of input signals. Control tape tension equals the control of output torque. With tension setpoint, tape speed setpoint, actual tape speed and spindle radius, we can calculate the current spindle torque by equation 4.1.

$$\tau_{ld} = \frac{T_{ref} R_{sp}\, v_{tp}}{v_{ref}} \tag{4.1}$$

The difference between current tension and setpoint is adjusted by a Proportional-Integral-Derivative (PID) controller. It is found in a wide range of applications for industrial process control. Approximately 95% of the closed loop operations of industrial automation sector use a PID controller. In MATLAB/ Simulink software, it is convenient to use the built-in PID block to adjust parameters based on environment. The discrete PID controller structure can be built as shown in figure 4-1.

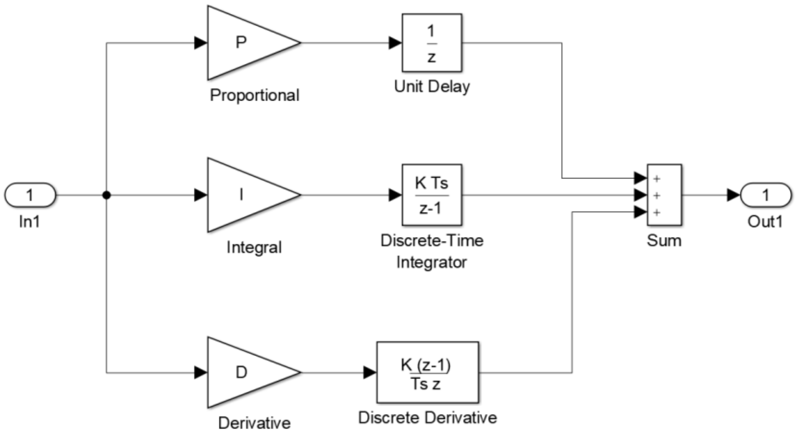

Figure 4-1. Discrete PID controller block

In this system, once the torque difference is detected, it will go through PID controller to give certain compensation, this signal will be sent to the motor module to instruct whether the motor need to provide or reduce the output torque. Figure 4-2 shows the control block of the whole system.

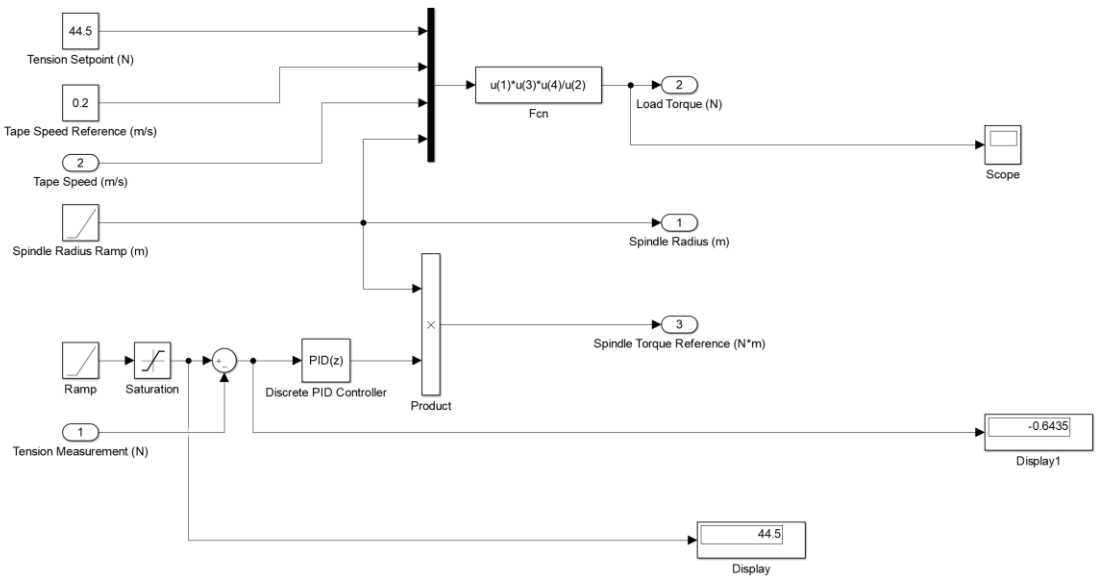

Figure 4-2. Spindle motor control module block.

4.2 Spindle Motor Drive

For motor drive parts a DC motor is used to simulate instead of a stepper motor which requires a more complex drive module. As discussed above, the compensation value of torque as an input signal connects to the motor model, which will output motor speed if we select and apply a load torque. Also, as calculated in chapter 2, we use a speed reducer block connected with the motor block as a gearhead of the spindle motor ($n_1 = 15$). We can then set the gear ratio and gearbox efficiency which is set as 95%, the work principle is shown in figure 4-3.

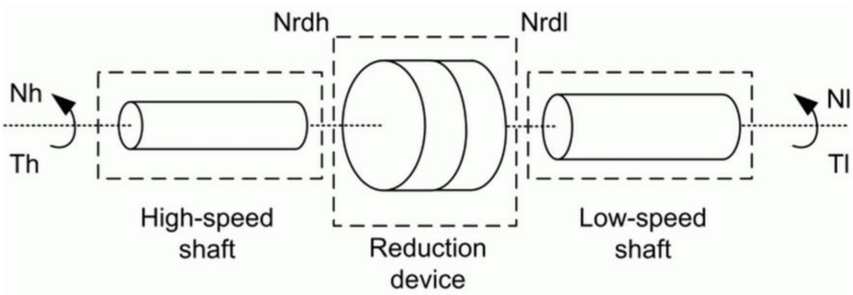

Figure 4-3. High-level schematic of speed reducer block.

The reduction device dynamics are governed by the equation 4.2.

$$J_{rdh}\ddot{\theta}_{rdh} = \tau_h - \frac{\tau_l}{\eta n} \tag{4.2}$$

Where

J_{rdh}: Inertia of the reduction device with respect to the high-speed side;

$\ddot{\theta}_{rdh}$: Acceleration of the high-speed side of the reduction device;

τ_h: Torque transmitted by the high-speed shaft to the input of the reduction device;

τ_l: Torque transmitted by the low-speed shaft from the output of the reduction device;

η: Efficiency of the reduction device;

n: Reduction ratio ($n \geq 1$).

The output speed N_{rdl}(the speed of the driving side of the low-speed shaft) of the reduction device is given by equation 4.3.

$$N_{rdl} = \frac{N_{rdh}}{n} \tag{4.3}$$

Where

N_{rdh}: Input speed of the reduction device (the speed of the loaded side of the high-speed shaft).

Therefore, the actual angular speed and torque compensation of the spindle as the inputs to this module. Eventually we gain the actual torque applied on the rewind (spindle). The block of the motor module is shown in figure 4-4.

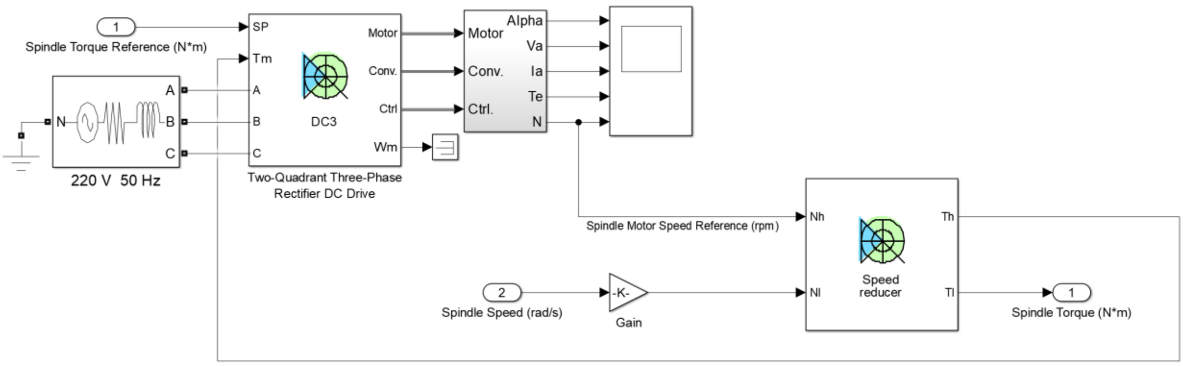

Figure 4-4. Motor drive module block.

4.3 Spindle Model Module

The spindle model module receives spindle torque and torque output from the motor. This is separated into three main parts for analysis. The basic structure of the spindle model is constructed by spindle state equation, spindle model and measurement modules. As shown in figure 4-5.

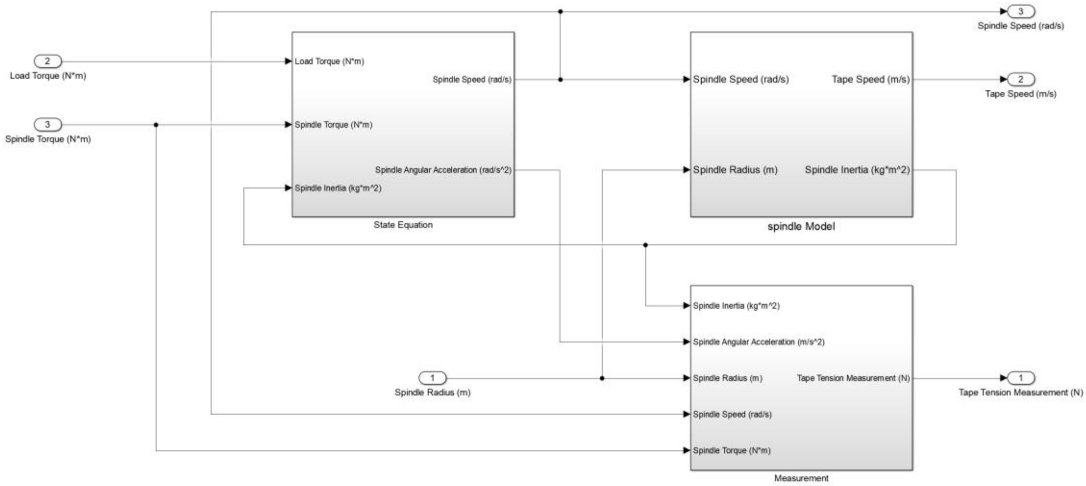

Figure 4-5. Structure of spindle model module.

State Equation Module

The state equation with applied torque and load torque is given by equation 4.4.

$$J_{sp} \frac{d\omega_{sp}}{dt} = \tau_{sp} - \tau_{ld} \quad (4.4)$$

The torque applied by motor τ_{sp} is zero for $t < 0$, and we assume that the motor inertia is negligible. For the input to the system the torque is considered, while the output is the angular velocity. Considering there is viscous friction applied by the bearings, as shown in figure 4-6.

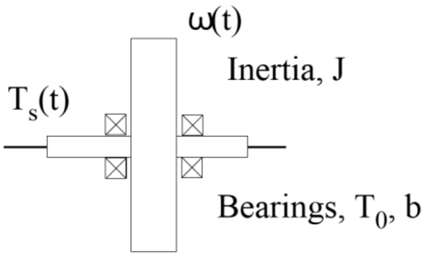

Figure 4-6. Motor attached to a shaft with viscous friction.

Assuming the friction has a linear relation with angular speed, then equation 4.4 can be expressed as equation 4.5.

$$J_{sp} \frac{d\omega_{sp}}{dt} = \tau_{sp} - \tau_{ld} - b\omega_{sp} \quad (4.5)$$

Where b is the viscous friction coefficient (units $N \cdot m \cdot s$). In our model, $b = 0.1 N \cdot m \cdot s$.

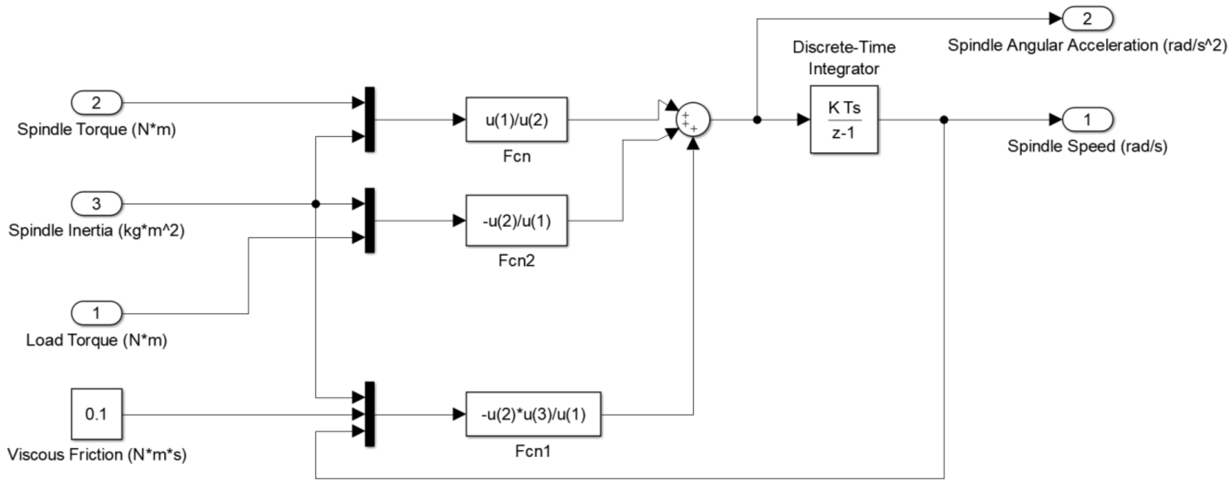

Figure 4-7. State equation block.

The state equation module can be drawn in figure 4-7. The spindle angular acceleration as output for further calculation is then considered.

Spindle Model

The spindle angular speed calculated from state equation block and spindle radius as inputs to spindle model part to calculate the current spindle inertia and tape pulling speed. As discussed in chapter 2, equation 4.6 given below can be used to calculate the spindle model inertia.

$$J_{sp} = \frac{1}{2}\pi\rho l(R_{sp}^4 - R_o^4) \tag{4.6}$$

Where

ρ: Tape density;

l: Length of rewind.

In this project, assume that we use polyethylene material tape, as it has a density range of 0.9 - 0.941g/cm^3 and above. It has a very low degree of branching and offers a significant improvement in tensile strength. [9] It can be seen that the inertia continuously changes due to the continuously inversing radius.

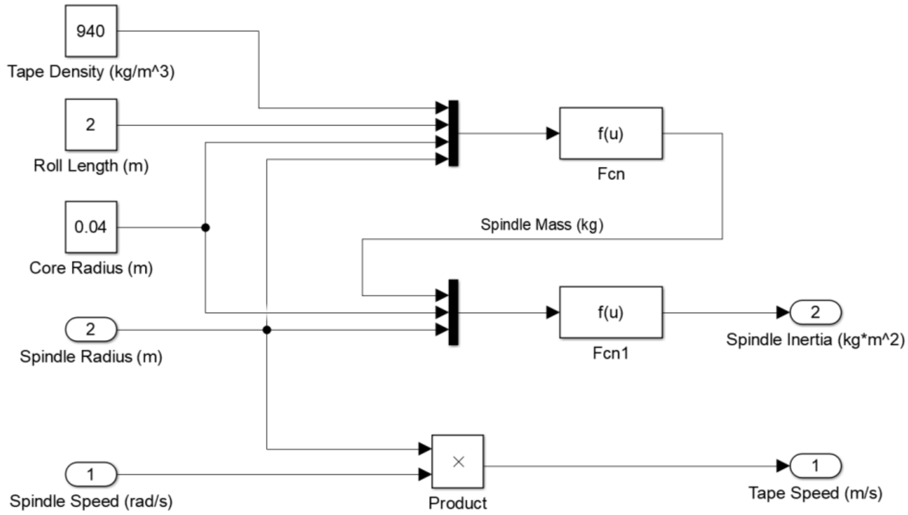

Figure 4-8. Spindle model block.

radius keeps increasing. Also, the linear speed (tape speed) is expressed by current radius multiplied by spindle angular velocity. Spindle model is shown in figure 4-8.

Measurement

In this module, we use all the outputs of the previous blocks as input signals to calculate tape tension, equation 4.7 is shown below.

$$T_{tp} = \frac{\tau_{sp} - b\omega_{sp} - J_{sp}\alpha_{sp}}{R_{sp}} \tag{4.7}$$

Figure 4-9 shows the measurement block. The output tension go back to control module to compare with the tension setpoint.

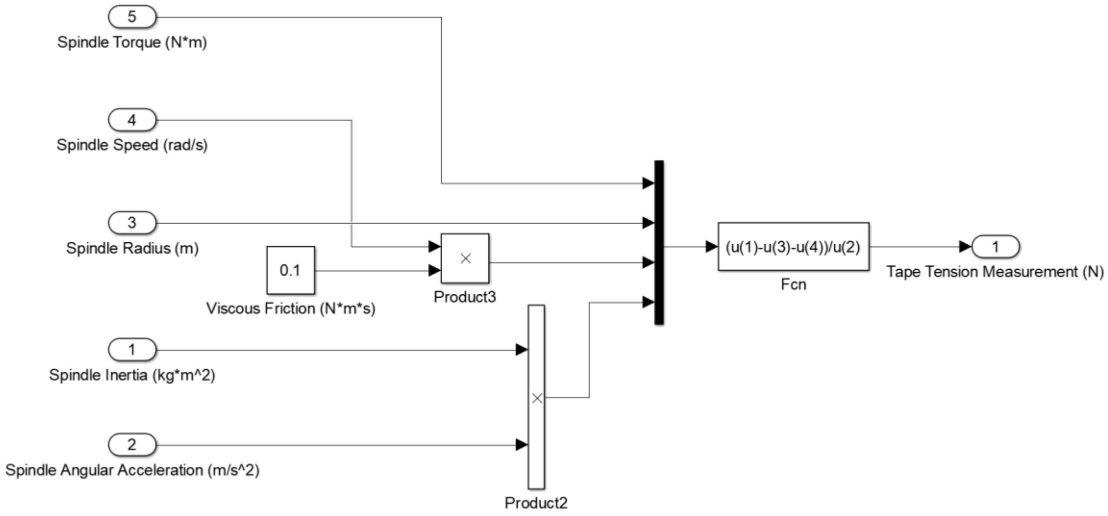

Figure 4-9. Measurement block.

4.4 System Model

So far, all the main parts of the spindle model system have been build and, connected together as shown in figure 4-10. Current tape tension and tape speed connect to control module as feedback signals, spindle angular velocity back to spindle motor drive module as input to change spindle motor's output torque.

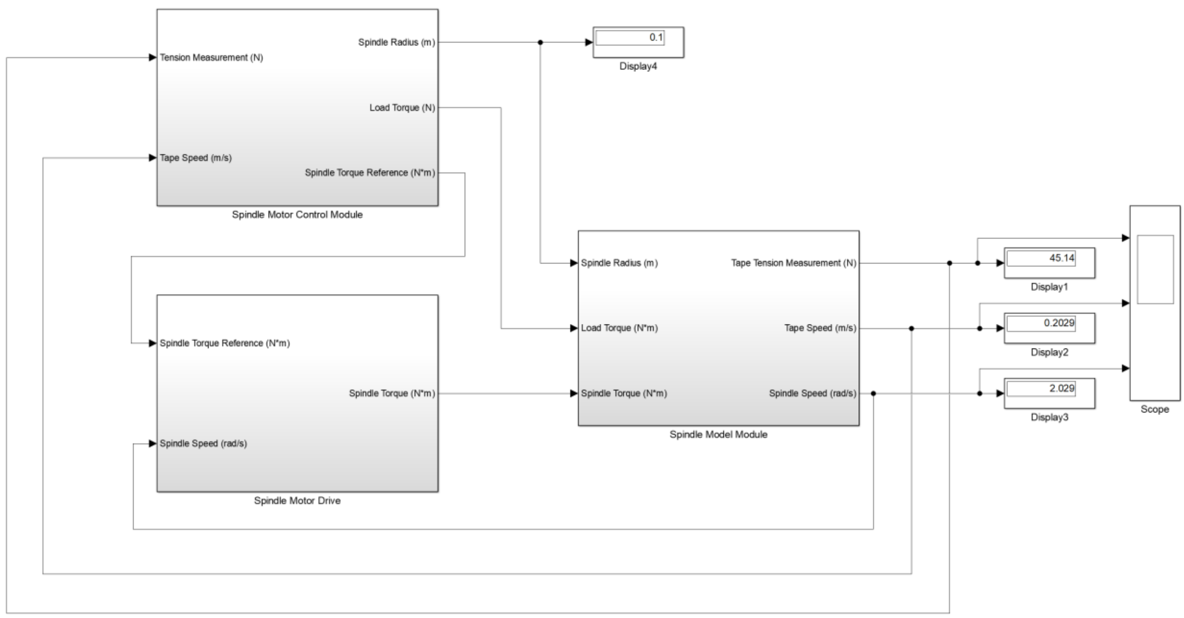

Figure 4-10. Spindle model system.

The whole system is run by adjusting the proportional parameter first. All the plots below are only run in 5s periods since the whole process is quite slow. We set the P = 1, P = 5, P = 10 separately when I = D = 0. The results are shown in figure 4-11.

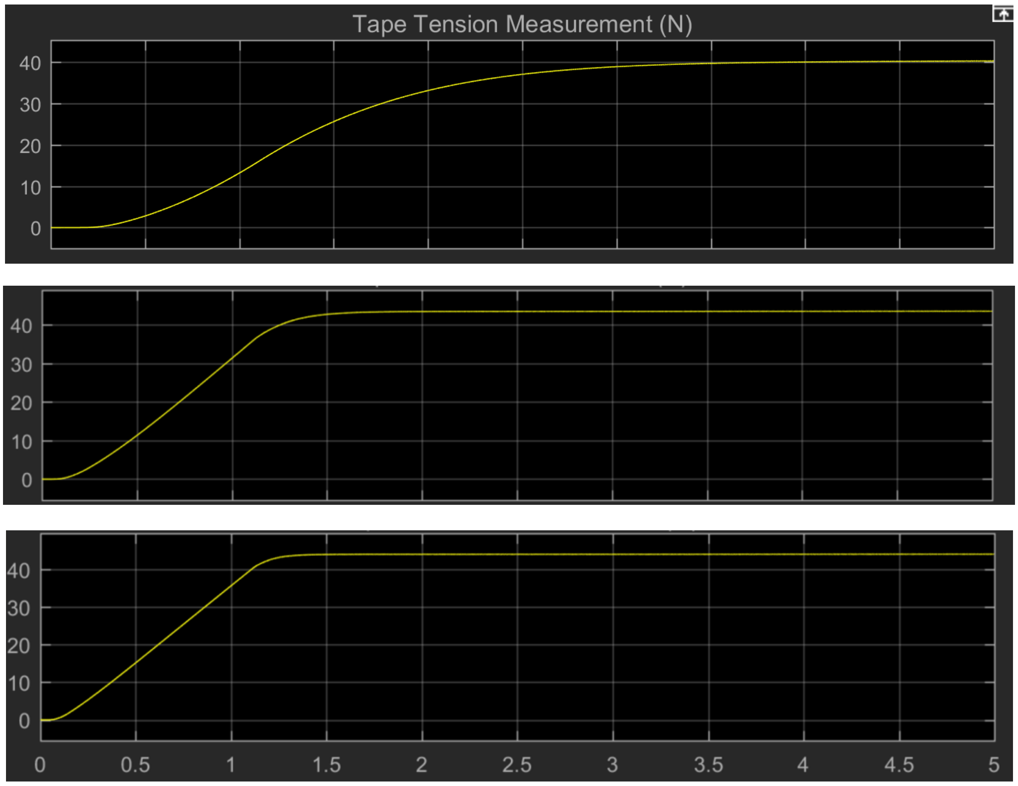

Figure 4-11. Tape tension curve at P = 1, 5, 10 (from top to bottom).

It's easy to tell that when proportional value increases, tape tension setpoint will be reached quicker and, the curve becomes increasingly straight. When P is set to 5~10, the final value is close to setpoint 44.5 N in 1.5s. However, if we keep increasing P, the time to reach the peak does not change as much. There is always an error that exists between the measurement and the setpoint.

Then add an integral parameter I to eliminate error caused by proportional control but, keep P = 5 and, set I = 0.5. The plot 4-12 shows the tension curve and final value is 44.52.

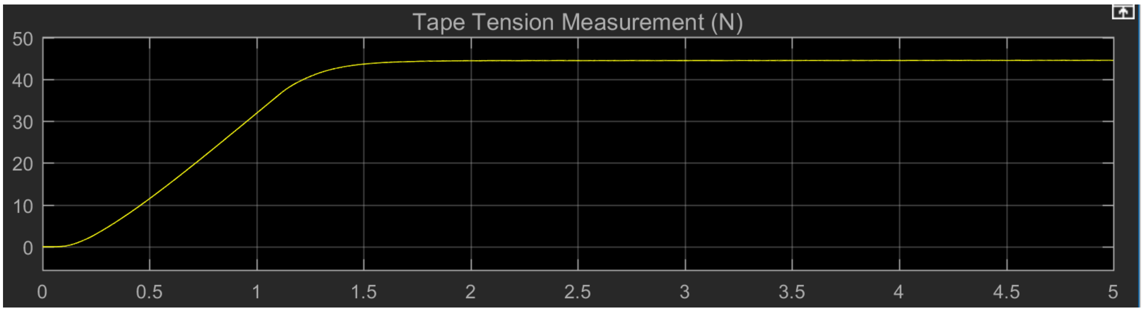

Figure 4-12. Tension curve in P = 5, I = 0.5 case.

When I is set to I = 1, the partial plot in figure 4-13 shows it has much more tension overshoot, the final value is 44.95, which takes longer than 5s to go back to the setpoint.

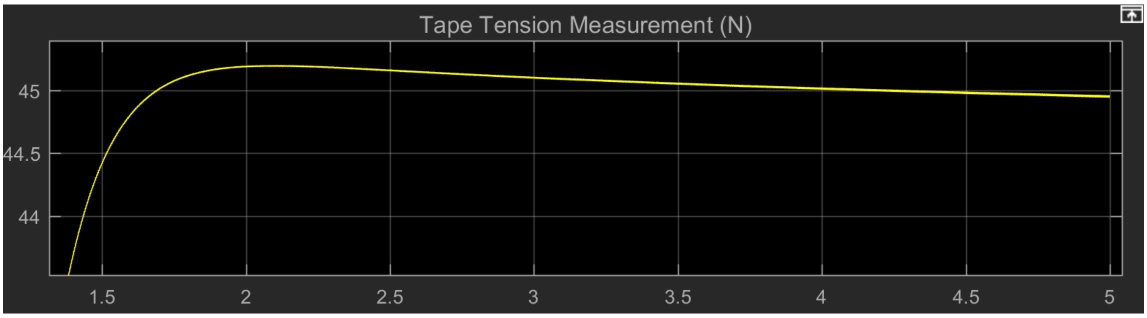

Figure 4-13. Partial tension curve in P = 5, I = 1 case.

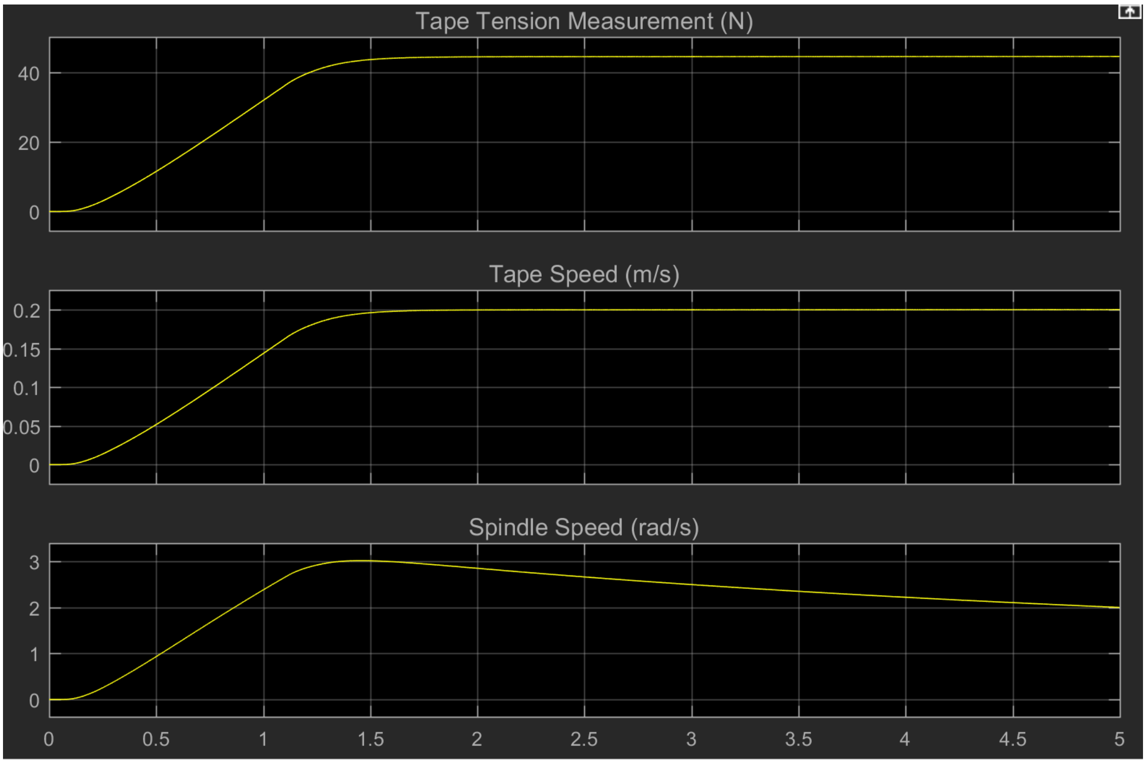

Figure 4-14. Tape tension, pulling speed and spindle speed curve (P = 5, I = 0.5, D = 0).

As expected, the overshoot will increase rapidly when once increases the integral value slightly. Therefore, the tension curve behaves best when P = 5, I = 0.5. Considering derivative parameter used more often in systems with time lag, we keep D = 0. The curves of tape tension, tape pulling speed and spindle angular speed are shown in figure 4-14.

In this project, the model shows mostly an ideal winding process, variation of tape radius and motor driver model is simplified. However, it is important to connect the simulation to the reality, it involves more complex problems when a real machine is built. Table 4-1 lists the hardware of winding machine includes motors, drivers, controller and sensors, these specific items are based on the calculation in previous chapters. The estimated funding on this project is near four thousand dollars, all the hardware materials in the table 4-1 can be considered for the future work and real machine implementation.

Hardware for Winding Machine Project			
Item	Numbers	Price	Total Cost
Spindle Motor	1	1936	1936
Tension Motor	2	91.8	183.6
Carriage Wheel Motor	1	140.3	140.25
Distance Sensor	2	34.95	69.9
Force Sensor	1	30.76	30.76
Motor Driver	1	384	384
Motor Driver	1	348	348
Controller	1	1000	1000
		Total	**4092.51**

Table 4-1. Hardware of winding machine.

CHAPTER 5 CONCLUSION

This paper analyzes the work principle of rewind, unwind and tension wheel during the winding process. Utilize the proper motor to input torque on rewinding spindle and explains the relation between carriage motor and spindle motor. To make the tape of the cylindrical winding product with high quality, it is critical to ensure it has constant tension applied on the tape in the winding process. After Researching and combining several papers, one can provide multiple methods to measure tension and control tension. In the simulation model, start with analyzing the winding model includes motor torque and dynamic variety of rewind inertia, the tension closed-loop control system is designed and implemented and, the system chooses a PID control strategy. The certain tape and speed will be achieved by changing PID parameters. However, once the tape tension is set to a new value, previous PID parameters are not available and need to adjust their values multiple times manually. Linear models for tape winding cannot predict tension very well and, methods provided by other articles to fix this default involve fuzzy control and machine learning. Roll-to-roll converting machine is also reasonable to be analyzed as a nonlinear MIMO system model. In hardware, stepper motors are selected instead of servo motors since the price of servo motors is usually twice higher that stepper motors, also, the stepper motors' position can then be commanded to move and hold at one of these steps without any position sensor for feedback.

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