Optimizing Tension Control in Center-Driven Winders

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Abstract
In a center-driven winder or unwinder, accurately determining the diameter of the roll is a key factor to the overall performance of the system. As the material is wound or unwound, constant tension of the web must be maintained. In order to maintain tension, two variables must be known: linear velocity of the web and the diameter of the roll. From that, rotational velocity of the roll or roll speed setpoint can be calculated. Web velocity is normally provided by the feedback device on the nip motor taking the web to/from the winder.

Diameter can be measured directly via a sensor or calculated by either a drive or an independent system using several available methods. Since no system of measurement or indirect calculation is perfect, the calculation produces an error between the ideal and real diameter of the roll. Without compensation, the resulting speed difference can cause a tension deviation, possibly producing a web slack or excessive tension that can result in deformation and a web break. For that reason, a tension control loop with tension sensor or load cell or position control loop with dancer system is used to detect and correct the undesirable deviation. A larger error results in larger correction taken by the tension controller.

Since a correction is done after the deviation has already occurred, there is a limitation of the winder performance in terms of maximum operating speed, build ratio and tension range. Improving diameter calculator accuracy limits the amount of correction the tension controller needs to do and raises system operational characteristics. With the advance in motion control systems, it is now possible to utilize drive technology, such as position information, to calculate diameter of the roll more accurate then ever.

The technology described in this paper is widely used across a number of industries, from paper to metal forming. There are three basic ways to implement web handling control: in the drive system, in the PLC or in the motion controller. Pre-packaged solutions, for easy implementation of full converting functionality, are available from a number of manufacturers.

Winder Control Concepts
There are different methods of control that can be applied to center-driven winders: torque or speed control, for example. This paper will concentrate on the theory of the speed based winder control, although many results regarding diameter calculation methods can be readily applied to torque control winders.

In a speed controlled center driven winder, a spindle motor performs two main functions:
- Matching linear velocity of the machine
- Maintaining constant tension in a web

Linear Velocity and Diameter Calculation
In order to match constant web velocity \( v \), spindle angular velocity must decrease as the diameter of the roll increases. The relationship between angular spindle velocity and surface web velocity is shown in Figure 1 below.
Machine velocity is derived from the nip roll motor that is part of the same drive control system or is measured by an externally mounted encoder. In order to derive correct angular rotation velocity of the spindle ($\omega$) a diameter (D) of the roll must be calculated or measured.

**Web Tension**

In a speed-controlled center driven winder two methods can be used to control tension:
- Load cell can be used to measure web tension. Tension controller then alters velocity of the spindle based on the load cell reading.
- A freely moving dancer arm mechanism with preloaded force can be used. Dancer position deviation feedback is used by the position controller to adjust angular velocity of the spindle.
**Technology Controller**

Both position controller for dancer based systems and tension controller for load cell based systems can be commonly referred to as a technology controller. A technology controller is a closed loop control system that applies correction based on the difference between the setpoint and actual values. Setpoint vs. actual difference is scaled by a factor called Proportional gain. An Integral and Differential component is applied as well. The term PID controller is also commonly used to refer to this calculation.

![Technology Controller Diagram](image_url)

**Methods of diameter calculation and measurement**

As indicated in the previous section, diameter of the roll is needed in order to correctly calculate angular rotational velocity of the spindle to match linear web velocity. Diameter calculation can be accomplished either by direct measurement or by drive system calculation.

**Direct Diameter Measurement**

Direct diameter measurement is performed via an ultrasonic sensor or a lay-on roll attached to the measuring device such as a potentiometer or an encoder. Direct measurement methods are subject to mechanical and electrical factors associated with operation and maintenance of measuring devices and the mechanics involved.

![Direct Diameter Measurement Diagram](image_url)
Drive-Based Diameter Calculation

Drive based methods of calculating diameter include material thickness addition, web velocity over winder shaft rpm \((V/n)\), integration of web velocity, and position based calculation. With all drive-based diameter calculation methods, an initial diameter setting is needed. Initial diameter can be determined one of the following three ways:

- Direct operator input
- Direct diameter measurement method
- In dancer-based systems, a displacement of the dancer vs. rotational angle of the spindle during tension-on procedure can be analyzed as shown in the Figure 5 below.

\[
r' \approx \frac{2x}{\theta}
\]

![Diagram of Drive-based Initial Diameter Measurement](image)

**Material Thickness Addition Diameter Calculation**

Material thickness addition is potentially the most precise method of diameter calculation. Thickness of the wound material is added to the diameter every revolution.

\[
D_{new} = D_{old} + \text{thickness}
\]

Calculation precision is dependent on three factors:

- Accuracy of the Initial diameter
- Accuracy of the specified web thickness
- Web thickness consistency of the material and the ability to build the roll at the specified web thickness. Air trapped between material turns will alter the roll diameter.

**Web Velocity over Winder Shaft Diameter Velocity Calculation \((V/n)\)**

In this method of calculation, diameter \((D)\) is determined by using the relationship between surface web velocity \((v)\) and angular velocity of the spindle \((\omega)\) using formulas

\[
(\omega = \frac{v}{r}, D = 2 * r)
\]

outlined in Figure 1. Instantaneous velocity values are used in the calculation.
Integration of Web Velocity

In this method of diameter calculation, velocity is integrated over time to determine the linear position of the web and angular displacement of the spindle.

\[ \theta(t) = \int \omega(t) dt \quad S(t) = \int v(t) dt \]

Then diameter is calculated based on web distance \( S \) and angular displacement \( \theta \) (refer to Figure 1 above):

\[ r = \frac{S}{\theta}, D = 2 \times r \]

Position-Based Calculation

With position-based diameter calculation, position is measured directly from spindle and nip roll displacement and diameter is calculated directly using \( r = \frac{S}{\theta} \) formula. Position reference must be available to perform this calculation.

Comparing Drive-Based Diameter Calculations

In order to analyze and compare drive-based diameter calculator methods, two factors need to be considered:

- Constant speed operation vs. acceleration profile
- Update frequency of the diameter calculator logic

Material velocity over winder shaft diameter \((V/n)\) calculation takes immediate snapshots of web and spindle velocity with no filtering of the signal built-in to the calculation. The signal is expected to vary during operation both at constant speed and during acceleration as modeled in Figure 6 and shown in Figure 8 and Figure 9.

![Figure 6 Material Velocity over Winder Shaft Diameter Calculation (V/n)](image_url)
As an improvement, Integral method of calculation provides transient response filtering by integrating velocity over the period of time. That produces a more stable and accurate signal, as compared to V/n. If velocity remains constant, the accuracy of the integral diameter calculation is comparable to the position based calculation (see Figure 8). During acceleration, when the velocity is constantly changing, the integral diameter calculator effectiveness is reduced. Increasing the sampling rate of the integration function increases the accuracy of the approximation of the actual position displacement.

Figure 7 shows the theory of increasing sampling time in the integration calculation. Figure 9 and Figure 10 demonstrate the effect of increasing the velocity sampling rate from 1ms to 6ms during acceleration on the actual machine. While at 1 ms, the integral performance is roughly identical to position based calculation: the 6ms trace shows integral calculation deviation during acceleration phase of the profile.

\[
\Delta s = v \Delta t, r = \frac{s}{\theta}
\]

**Figure 7** Integration of Web Velocity

Web Velocity: 100 m/min
Update time: 1 ms
Acceleration profile:
1. 50 m/min
2. acceleration to 300 m/min
3. deceleration to 10 m/min

Diameter calculator execution time: 1ms

Figure 9 Diameter Calculator: Acceleration, 1ms update time

Acceleration profile:
1. 50 m/min
2. acceleration to 300 m/min
3. deceleration to 10 m/min

Diameter calculator execution time: 6ms

Figure 10 Diameter Calculator: Acceleration, 6 ms update time
Conclusions:
1. At constant speed, position and integral methods of calculation offer greater stability and accuracy of the diameter calculation.
2. During acceleration, stable and accurate diameter output can be achieved with the integral method of diameter calculation by executing integration logic at a faster rate.
3. Position-based diameter calculation is largely independent of acceleration and sampling rates, producing the most accurate and stable diameter output.

Interaction between diameter calculation and technology control
Instead of considering a diameter calculator function as part of the speed setpoint branch determining the rotational speed of the drive, it would be more appropriate to think of it as another control loop. The interaction between diameter calculator and the controller can be better explained in a series of steps:

**Step 1:** Roll diameter is calculated and spindle velocity is set. For the sake of this discussion, it is assumed that diameter and velocity are derived precisely without outside influences or errors. The spindle turns at an exact specified speed: actual speed of the motor = setpoint speed.

**Step 2:** As the winder diameter gradually changes, the diameter calculation remains unchanged as it relies on the feedback (speed or position) from the motor.
Step 3: An increasing error between actual and calculated diameter produces speed deviation which results in the deviation of the dancer.

![Diagram](image13)

Figure 13 Diameter and Tension Controller: Step 3

Step 4: Dancer deviation is detected by the tension controller. Correction velocity based on PID controller parameters is added to the setpoint channel. Motor speed setpoint and actual velocity is altered.

![Diagram](image14)

Figure 14 Diameter and Tension Controller: Step 4

Step 5: Modified velocity and position is read by a diameter calculator function, producing new diameter value and new speed setpoint.

![Diagram](image15)

Figure 15 Diameter and Technology Controller: Step 5
**Step 6:** It is important to mention that at this point, the technology loop is still applying correction resulting in the overcorrection.

![Diagram](image)

**Step 7:** Technology controller gradually restores the dancer to the neutral position. Time must be allowed for the technology controller to settle prior to calculating a new diameter value. The cycle repeats from **Step 2**.

![Figure 16 Diameter and Technology Controller trace](image)
The following conclusions can be made based on this sequence analysis:

1. Diameter calculation must be less dynamic than technology controller. If the diameter calculator is as dynamic or more responsive than the technology controller, it will respond to the correction in Step 6 with a new diameter value. Continued interaction will produce an oscillation between technology controller and diameter calculator as shown in the Figure 17 below.

![Figure 17: Oscillation example between diameter calculator and technology controller](image)

2. Within the limits of conclusion 1 diameter change steps should be as small as possible to minimize the velocity step disturbance produced in the speed and technology controller.

Conclusion

In a center-driven winder or unwinder, accurately determining the diameter is a key factor to the overall performance of the system. With direct measurement methods susceptible to real-world mechanical and electrical factors, drive-based diameter calculation methods can increase the reliability and accuracy of the system. While material thickness addition calculation is theoretically the most accurate, it relies on outside factors much like direct measurement methods. Other diameter calculation methods available are: web velocity over winder shaft velocity (V/n), integral, and position.

When using drive-based diameter calculation at constant velocity, position and integral methods offer greater stability and accuracy of the diameter calculation. During acceleration, stable and accurate diameter output can be achieved with the integral method by execution integration logic at a faster rate. Position-based diameter calculation is largely independent of acceleration and sampling rates, producing the most accurate and stable diameter output of all drive-based diameter calculation methods.

All drive-based diameter calculations described rely on the technology loop controller to operate properly. Two loops interact and influence each other during operation. While the diameter calculator needs to update diameter value fast enough to minimize the disturbance from the velocity step response, it must be less dynamic than the tension controller in order to prevent oscillation between both processes.
The technology described in this paper is widely used across a number of industries: from paper to metal forming. There are three basic ways to implement web handling control: in the drive system, in the PLC, or in the motion controller. Pre-packaged solutions, for easy implementation of full converting functionality, are available from a number of manufacturers.

![Figure 18   Web Handling Implementation Example](image)

References
1. William B. Gilbert - Methods of Diameter Determination for Center Driven Unwinds and Rewinds, 2010