Methods of Diameter Determination for Center Driven Unwinds & Rewinds

Advantages & Disadvantages

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The Importance of Accurate Diameter Determination

Accurately determining the diameter of a center driven winder or unwind is one of the most important tasks of the tension control system. In most drive tension control systems, the highest percentage of the torque or speed command signal (typically ~ 95%) comes directly from the measured or determined diameter value. Then the tension sensor, either dancer or loadcell, will provide only the remainder of the command to the driven spindle.

In a torque regulated tension control system, the diameter is used to provide the inertia compensation for acceleration and deceleration, and also the torque or tension setpoint. In a speed regulated tension control system, the diameter is used for the inertia calculation that adjusts the speed loop gain, for scaling the tension loop gain and for scaling the velocity feedforward setpoint to the drive. In winders that require taper tension, an accurate diameter calculation is required to modify the tension setpoint. Most center driven spindles with large build ratios will also require an adaptation of the tension loop gain in respect to the diameter. Gap winders commonly will wind with an air gap of 0.25 in. or less between the lay-on roll and the winding roll; here the accuracy of the diameter calculator is also very critical. Other functions that require accurate diameter calculation are the accurate positioning of a turret when splicing and loading rolls, stopping at a preset diameter for manual slicing.

Tension control systems will always face the demands to push the limits with wider tension ranges, wider speed ranges and wider roll diameter ranges. Speed and production rates are continuously being increased. As these things happen, accurately determining the diameter of a center driven winder or unwind become more and more critical. Understanding this, it can be confidently stated that tension control accuracy and most other winder functionality can be greatly improved by focusing on the accuracy of the diameter calculator.

What follows in this paper is a review of the four commonly used methods of determining the diameter in center driven tension control systems, the introduction of an improved method that can be simply implemented in most existing controllers with existing technology, and an even more precise variant that is well suited for the latest features in new drive and automation technologies.

Commonly Used Diameter Determination Methods

Of the four commonly used methods, the first two are measurements from sensors, the others are calculations made from drive or tension control system data;

- Lay-on Roll Measuring Arm
- Direct Diameter Sensor
- Web Velocity / Winder Shaft Rpm (v/n)
- Roll Turns & Web Thickness
Lay-on Roll Diameter Measurement

The use of a Lay-on Roll for diameter measurement is probably the earliest implemented method of measuring a roll diameter. It is still used in some systems, primarily in simple and mechanical tension control systems. This method consists of a Rider or Lay-on roll, (even sometimes called a follower arm) that contacts the outside diameter of the roll with a wheel or an idler roll. The wheel or idler roll is mounted to a pivoting arm. The pivoting arm is loaded against the roll and a sensing device is mounted to the pivot point. The measured angle from this sensor is then converted to the roll diameter. The sensing device is usually a potentiometer, but analog proximity sensors, hall-effect sensors or even pulse encoders have all been applied here with good results. This method is typically used in braked unwinds or non driven tension control systems.

Lay-on Roll Advantages:
- Simple and robust.
- Easy setup
- Relatively low maintenance.
- Diameter value does not require motion.

Lay-on Roll Disadvantages:
- The roll or wheel must contact the material, this can be an issue for some materials that are slippery or have a coating that can not be contacted.
- The Lay-on Roll mechanics can interfere with roll changing or machine maintenance.
- Issues with out-of-round rolls cause inaccurate diameter readings.
- Mechanical system, and will require some maintenance, affects machine design.
- May limit the roll size on the machine.
- The sensor output is not truly proportional to diameter. The arm angle must be taken into consideration.
- Must be loaded against the roll (pneumatic, other force).
- Will require a filter for use in most systems.

Fig. 1; Lay-on Roll Diameter Measurement
Direct Diameter Sensor Measurement

The Diameter Sensor measurement is similar to the Rider Roll as it is an external device that takes a direct measurement of the diameter from a sensor. However, here the sensor makes a reading of the diameter that is proportional and can in most cases be used directly from the sensor. Typically this sensor is an ultrasonic device, but other analog optical and even laser sensors have been used. In the case of the ultrasonic sensor, it emits a signal that travels to the rolls surface, bounces off and returns to the sensor. The sensor then measures the time it takes for the signal to return to the sensor and calculates a distance. The distance then is a linear value proportional to the radius of the roll. This method is typically used in braked unwinds or non driven tension control systems, and driven systems for starting diameter only.

Direct Diameter Sensor Advantages:
- Relatively low maintenance
- Provides a linear output proportional to roll diameter.
- No material contact with the roll.
- Outputs can be connected directly to the drive or controller.
- Diameter value does not require motion.

Direct Diameter Sensor Disadvantages:
- The measurement can be affected by moving air.
- The measurement will be affected by objects between the roll outer diameter and the transducer.
- Must be calibrated with each installation.
- May need periodic maintenance and calibration.
- Susceptible to dirt and dust.
- Certain low density materials may absorb the ultrasonic signal.
- Mounting is critical and if the sensor is disturbed it will not operate properly.
- Prone to damage from roll changes.
- Typically does not work well with out of round rolls.
- Susceptible to temperature drift.
- Will require a filter for use in most systems.

Fig. 2; Direct Diameter Sensor Measurement
**Web Velocity / Winder Shaft Rpm (V/n)**

Web Velocity / Winder Shaft Rpm (V/n) is probably the most common used method of determining roll diameter for center driven spindles. This method is a calculation from the measurement of two velocities and not a direct measurement. The controller requires the rotational speed of the spindle and the linear velocity of the web. Here the diameter of the roll is proportional to the velocity of the web divided by the rotational speed of the wound roll. This method provides a good, steady state, diameter value. However, in most cases the diameter calculation of this mode will not be very accurate while accelerating and decelerating. A holding circuit is employed below a minimum speed. Most current drive tension control systems will use a variation of this method.

**Web Velocity / Winder Shaft Rpm (V/n) Advantages:**
- Uses existing machine hardware.
- The calculation is directly proportional.
- No contact to roll issues.
- Works directly with drive or controller software to provide alarm setpoints.
- Good steady state calculation (even with out of round rolls).
- Simple calculation.

**Web Velocity / Winder Shaft Rpm (V/n) Disadvantages:**
- Must be above minimum line speed for calculation.
- Filters required for output smoothness.
- Filter changes may be required for changes in material thickness (fast diameter changes).
- Accuracy during acceleration and deceleration.
- Requires a minimum speed setpoint and diameter hold.

Fig. 3; Drive & Tension System using V/n Diameter Calculation
Fig. 5; V/n Math

\[ v = \omega \cdot r = 2\pi n \cdot r = \pi n \cdot D \]

\[ \Rightarrow D = \frac{v}{\pi n} \Rightarrow D \sim \frac{v}{n} \]

Fig. 6; Typical Block Diagram, V/n Function

Legend:

V: Line speed
n: Rotational speed
D: Diameter
**Roll Turns & Web Thickness**

Counting Roll Turns and adding increments of web thickness can be the most accurate method of all the previously discussed methods; however this is highly dependent on very closely meeting multiple criteria. This method counts the incremental addition of the spindle revolutions and adds a unit of the web thickness for each revolution. This means that this method is in effect an open loop mode of calculation. The determined accuracy depends on the accuracy of the web thickness input variable and the ability of the system to maintain roll hardness and limit air entrapment. This may mean a lay-on roll would be required. If all conditions are met, counting roll turns can provide a stable diameter value regardless of speed. This method is typically used with metal webs or foils that have a precise thickness and have no issue with air entrapment between layers.

**Roll Turns & Web Thickness Advantages:**
- Can be the most accurate calculator.
- Not susceptible to acceleration / deceleration / speed disturbances.
- Does not require filtration.

**Roll Turns & Web Thickness Disadvantages:**
- Open Loop System.
- Can require a rider roll to eliminate air entrapment.
- Web thickness variable must be accurate.
- Difficult to use with Taper Tension
- Requires an accurate starting diameter (may need to be used with a direct sensor).

Fig. 7; Roll Turns Calculation, New Diameter = (Old Diameter + (Web Thickness * 2))

Fig. 8; Roll Turns Calculation, Typical Function Block
An Improved Method of Diameter Determination

An improved method can be applied to most tension control systems that offers several benefits over the common diameter determination methods. There are two possible adaptations of the method; the first uses the integral of the velocities of the web and the winder.

- Integration of Web Velocity / Spindle RPM (speed based systems)

Integration of Web Velocity / Spindle RPM

Using only the velocity information from the system controls, this method has many advantages over all of the previous diameter determination methods. In the integration mode, the position of the web and the angle of the spindle are integrated from the speed of the line and the angular velocity of the spindle. These positions are updated at a predetermined number of spindle revolutions. Interpolation is then done between the old and new values. The benefit of this method is its ability to actually track the diameter rather that looking at individual snapshots of diameter. Tracking or obtaining a “history” of the diameter provides increased stability of the measurements without the filtering that is sometimes required in the v/n method or direct measurement sensors. The added stability of this method can be also seen during acceleration, deceleration and at standstill. In addition the diameter hold is not required.

Integration of Web Velocity / Spindle RPM Advantages:
- More accurate than (v/n) during acceleration / deceleration / speed disturbances.
- Does not require filtration.
- Can be used to also determine starting diameter (Actual position mode).
- Diameter hold not required.

Integration of Web Velocity / Spindle RPM Disadvantages:
- Can be improved further in a motion control system (using actual positions vs. integration).

Fig. 9; Integration of web velocity / spindle RPM Block Diagram

![Block Diagram Image]
Actual Web Position / Actual Spindle Position Mode

Motion controllers and some drive control systems can provide the actual positions of axes. These systems can implement a further adaptation of this method by using the actual position of web and roll providing even more accuracy in the diameter determination. In addition, using actual positions permits a unique way of determining the starting diameter input to the control system, improving accuracy and eliminating troublesome machine components.

- Actual Web Position / Actual Spindle Position (motion based systems)

Starting Diameter Calculation using Position of Web & Spindle

Actual position can be used to calculate the starting diameter as well. Here the positions of the spindle and dancer are evaluated at empty and full dancer. The result is an extremely accurate starting diameter.

For a single wrapped dancer an example starting diameter calculation follows;

\[
\text{Spindle Starting Diameter} = \text{angle factor} \times (\text{dancer outer diameter} + \text{dancer inner diameter}) \times (\text{dancer ending position} - \text{spindle starting position}) / (\text{spindle end position} - \text{spindle starting position})
\]

Fig. 10; Starting Diameter determination

It is preferable to apply this method with encoder feedback on the dancer; however an analog device could be implemented as well. The encoder does offer several benefits, including the digital accuracy of the actual position change and the precise accuracy in determining the start of motion for counting.
Performance Results for Integration Mode

The following test results were achieved on a cantilevered bidirectional lab line consisting of two spindles and a vacuum roll main drive section. The integration mode of diameter calculation was implemented in the tension control system. For the test, the machine was run in an “AUTO” or reversing mode. The machine would accelerate to set line speed, stopping after at a preset minimum diameter on the unwind spindle. Next the tension is disabled, and re-enabled after a wait time. The machine would then switch web direction, restart and run at set line speed until the opposite spindle reached preset minimum diameter.

Machine Parameters:
- Line Speed 1500fpm (457M/min)
- Acceleration 500fpm/sec

Test Results:
- Stopping Position Error: +/- 1.0"
- Starting Diameter in reference to the last running diameter: +/- .5mm

Actual results of diameter determination for all of the previously discussed modes can be seen on Figure 11. The Integration of web velocity / spindle RPM mode can be seen as the green trace. Here this method shows improved calculation during the line acceleration and deceleration. In the magnified section is it can be seen that the calculation is also smoother than the (v/n) method during steady state running.

Fig. 11; Trace Recording of Diameter Determination Modes
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