Designing Drive Systems for Low Web Speeds
Web Tension Control at Low Speeds

Very low web speeds can provide challenges to implementing drive systems with accurate tension control.

Mainly, the issues relate to implementation of torque regulated tension control through high ratio gearing.

The following will be a quick review of the basics of center-driven tension modes, a look at the issues confronting high ratio gearing by working through a machine design example.

Then, a review of the solutions that current drive and motor technology can offer in improving tension control and solving the other issues inherent to systems that use high ratio gearing.
Center Driven Tension Control Overview

- TORQUE LIMITING
- INDIRECT TORQUE
- SPEED SETPOINT CORRECTION

Center Driven Tension Control
**Indirect Torque Control**

Is technically the simplest, but the least accurate of the modes. Indirect control does not make use of a tension feedback sensor. The tension control is open loop, directly based on the tension setpoint, factored by a measured or calculated diameter. Inertia and friction compensation may be a feature.
**Torque Limiting Control**

Is closed loop, based on the tension setpoint reference, factored by the actual diameter and compensated by the actual tension error through a PI (tension) control loop as a rotational force. Inertia and friction compensation are normally a feature.
Tension control modes – *Speed Setpoint Correction*

**Speed Setpoint Correction Control**
Is closed loop, based on the actual web speed reference, factored by the actual diameter and compensation by the transformed tension error through a PI (tension) control loop as a speed setpoint addition.
Determining the correct Tension Control mode

The selection of the center driven tension control mode can be influenced by several factors, including machine specifications or design, the type of tension sensor used.

Normally the determining factor will be the compliance of the web.

The modes of **torque** control / limiting are commonly implemented when the web material has a very low compliance or is “non-extensible”, e.g. heavy paper, steel, aluminum or other metals or foils.

The mode of tension regulation via **speed correction** is ideally implemented when the web is compliant or “extensible”.
In the engineering of web handling drive systems the traditional practice is to optimize the drive and motor sizes as close as possible to the web power requirement.

\[ \text{Optimum Gear Ratio} = \frac{\text{Optimum Motor Speed RPM}}{\text{Maximum Load Speed RPM}} \]

This is done by selecting a mechanical gear ratio that will enable the motor to run as close as possible to its base speed (synchronous motor) and well into the constant power range (when an induction motor is used).

The optimum gear ratio is determined by;
Optimum Motor Speed RPM / Maximum Load Speed RPM
Drive Sizing Overview

Two Main Criteria

Max Torque at Full Roll
Max Torque at Full Roll (in. lbs) = \((\text{Full Roll Diameter (in.)} / 2) \times \text{Maximum Web Tension (lbs.)} / (\text{Gear Ratio} \times \text{Gearing Efficiency})\)

Max Speed at Core
Max Speed at Core (RPM) = \(\text{Maximum Web Speed (FPM)} / ((\pi \times \text{Core Diameter (in.)}) / 12) \times \text{Gear Ratio}\)
The gearbox selection will determine efficiency or friction losses. Gearbox efficiency is the ratio of the output power (power transmitted through the gearbox as usable work) to the input power.

Typical gearing options are: Planetary, Helical, Worm and Pulley/Timing belt.

Generally planetary gear boxes are limited to 100:1 ratio, with about a maximum ratio of about ~8:1 per stage (there are some exceptions to this rule). Efficiencies for planetary gearing can be considered at ~90-95% per stage.
Planetary boxes are available in inline and right angle and can be considered for ratios up to 100:1
For gear ratios over 100:1, the options are typically multistage worm, helical or combination gearboxes.
Reference Machine Example

- Traditional Design
- Alternative Concept

Issues
Solutions
Consider a machine with three driven sections.

The cooling drum is the system master. The unwind and winder spindles are tension controlled with tension feedback from load cell transducers.

The web material being transported is a stainless steel foil.

Since the web is non-extensible, the mode of tension control for the spindles will be considered as Torque Limiting Control.
Power requirements from the specifications:
Max Web HP = (10 PLI * 14 inches) * 12.00FPM / 33,000 = 0.1508HP

Considering the very low power requirements of this system and that the industry tend to use synchronous servo motors in the drive systems when power requirements are at fractional HP and below, we will consider synchronous servo motors for each axis. This type of motor/drive system fits with industry practice. Servo motors in this size range will typically have a rated or maximum speed of 4500 RPM to 6000RPM.
Step 1: Gearbox Selection; Determine the spindle gear ratios (for a power optimized system) by Max Speed @ Core OD.

Max RPM @ Core =
Max FPM / (Π * (Core Dia. “/ 12)) = 12.00 / (Π * (6.75” / 12)) = 6.79 RPM

Considering a 4500 RPM motor we find an optimized Gear Ratio =
4500RPM / 6.79 RPM = **662.73:1**

For this example we will consider a gearbox ratio of 650:1. This ratio will set the speed at the motor.
Choices for gearboxes in the range of 650:1 are limited and will require the selection of a multi-stage gearbox to achieve a ratio of that magnitude. We can consider that the typical efficiency of a multi stage gearbox with a ratio of 650:1 will be in the area of ~33%.

Max Motor Speed at Core (RPM) =
Maximum Web Speed / ((\(\pi \times \text{Core Diameter}^{\prime\prime}\)) / 12) \times \text{Gear Ratio}
12.00 fpm / ((\(\pi \times 6.75^{\prime\prime}\)) / 12) \times 650.00 = \textbf{4413.90 RPM}

Min Speed motor at Full roll (RPM) =
Maximum Web Speed / ((\(\pi \times \text{Core Diameter}^{\prime\prime}\)) / 12) \times \text{Gear Ratio}
0.10 fpm / ((\(\pi \times 20^{\prime\prime}\)) / 12) \times 650.00 = \textbf{31.04 RPM}
Traditional Design Review (Motor Selection)

Step 2: Motor Selection; Determine the motor torque requirements at core & full roll

Max Torque at Core (in. lbs) =
\[ \left( \frac{\text{Core Diameter}}{2} \right) \times \left( \frac{\text{Maximum Web Tension}}{\text{Gear Ratio} \times \text{Gear Efficiency}} \right) \]
\[ \left( \frac{6.75}{2} \right) \times \left( \frac{140}{650 \times 0.33} \right) = 2.20 \text{ lbf-in} \]
(Note: a system with 90% efficiency would require 0.807 lbf-in at core)

Max Torque at Full Roll (in. lbs) =
\[ \left( \frac{\text{Full Roll Diameter}}{2} \right) \times \left( \frac{\text{Maximum Web Tension}}{\text{Gear Ratio} \times \text{Gear Efficiency}} \right) \]
\[ \left( \frac{18}{2} \right) \times \left( \frac{140}{650 \times 0.33} \right) = 6.53 \text{ lbf-in} \]
(Note: a system with 90% efficiency would require 2.39 lbf-in)
With these load criteria we can consider a synchronous motor with a minimum of; 2.20 lbf-in of torque at the maximum speed at core and, 6.53 lbf-in of torque at min speed @ full roll.

Based on the data, we select a standard motor rated at (1.3Nm) 11.5 lbf-in @ 6000RPM

As a result of the losses of the high ratio multistage gearbox the motor size has tripled from ~2.15 lbf-in to 6.53 lbf-in In this manner, the friction losses of the gearbox isolate the motor from the load.
In the direct torque control mode only this small component of the tension control signal is active, or supplied by the tension controller.

The majority of the tension setpoint is provided from the setpoint modified by the actual diameter and FF components.

The active portion of the tension control signal will be no more than about 5% of the full torque signal.

Also consider also that the friction losses are not static and will vary with time at a constant speed, they will also vary with speed, and load. The tension control system has to work through the dynamic peaks and valleys of the losses.
Active Torque Control Component to Losses

The torque required to produce max tension without considering loses is **2.15 lbf-in**

Giving an active tension control component of;

\[
0.05 \times \text{Max Tension Control Requirement} = 0.05 \times 2.15 \text{ lbf-in} = \mathbf{0.1075 \text{ lbf-in}}
\]

With friction losses of \((6.53 \text{ in. lbs} - 2.15 \text{ lbf-in} = 4.38 \text{ lbf-in})\) **4.38 lbf-in**

The output related to the losses is over 40 times the magnitude of the active tension control component output. \((4.38 \text{ lbf-in} / 0.1075 \text{ lbf-in}) = \mathbf{40.74}\)

For effective tension control in the direct torque control mode, the active tension control torque signal component should be at least equal or greater to the torque required to overcome the gearbox losses.
Tension Error from Torque Ripple

Significant tension error can be caused from the motors inherent torque ripple when factored through a high gearbox ratio.

This relates to $650/1 \times .02875 \text{ lbf-in} = 186.875 \text{ lbf-in}$ on the output of the gearbox, and $186.875 / 10 \text{ in. (full roll radius)} = 18.687 \text{ lb}$ of open loop tension disturbance on the web at full roll.

Consider also how an oversized motor will add to the open loop tension error induced by the motor. Additionally, external web tension disturbances will also manifest through the system in the same manner.

Synchronous servo motors can have a typical torque ripple from $\sim 2.5\%$ to $< 1\%$ of $M_0$ or the rated motor torque (worst case).

In the initial example, the selected motor has a rated torque of $11.5 \text{ lbf-in}$

Considering a torque ripple of $2.5\%$, the ripple at the motor shaft will be $\sim .025 \times 11.5 \text{ lbf-in} = .2875 \text{ lbf-in}$
Additional Issues – High Ratio Gearing

**Back-Driven Efficiency:**
High ratio gearing can have a much worse efficiency from the load side in comparison to the input, that in effect isolates load changes from output shaft significantly.

**Backlash and Compliance**
Any lost motion between motor and load, be it backlash or compliance will have negative effects on the control of the load. The more mechanical sections, meaning couplings, gearbox stages, etc. in the system mean additional compliance and backlash.
Additional Concerns – High Ratio Gearing

**Dynamic Performance**
There are always disturbances in the system. They can come from torque ripple, out of round rolls, tuning, etc. It is possible for a system that is geared to match the lowest web speed to not have enough dynamic response to compensate for the natural disturbance.

**Excess Output Torque from motor over sizing**
As ratios increase, any additional torque in the selected motor size from optimal can raise the issue of too much output torque at the output of the gearbox. The outcome can be machine damage with web jams or web breaks.

*(In the initial example the motor torque requirement was 6.53 lbf-in and the selected motor was 10.5 lbf-in.)*
An Alternative Solution - *Low Ratio Gearing*

Utilizing the lowest possible gearbox ratio or direct drive systems if practical can help to eliminate the following issues related to High Ratio Gearing;

- Load isolation through friction losses
- High Losses to active tension control component ratio
- Torque error magnification
- Additional detailed issues

Recommendations for gearing when required would be to consider an inline single stage planetary gearbox or timing belt. When considering a timing belt the limiting factor will be the distance between pulley centers. In most cases ratios in the range of 4:1 or less will be the maximum for timing belt gearing arrangements.
High resolution motor feedback encoders are essential to improving the low speed regulation of drive systems. And make possible speed regulation of fractional RPM.

The technology is not new, but still needs to be recognized in many sectors.

With the availability of the Sin/Cos optical encoders, feedback resolution has been increased from thousands of counts per motor revolution, to ~4 million counts per revolution for a 22 bit encoder to 16 million counts per revolution for 24 bit encoders.
SIN/COS Encoder Overview

- **2048 periods per revolution**
- **Sine track**
- **Cosine track**
- **Fine resolution of the analog signal with** $V_{pp} = 1V$ **using A/D conversion**
  - typical: **2048 pulses per sine period**
- **Light source (LED)**
- **Condenser**
- **Scanning plate**
- **Coded disk**
- **Photo elements**
- **Typical resolution:**
  - $2048 \times 2048 = 4.19$ million S/R
- **Accuracy:** approx. 40″ (angular seconds)

**Zero mark = reference mark**
An Alternative Solution – Encoder Resolution

The higher the resolution of the motor feedback sensor, the lower the speed that the drive system can effectively regulate.

As a conservative rule of thumb, we can consider the following minimum regulated speed for the following encoder types.

<table>
<thead>
<tr>
<th>Encoder Type</th>
<th>Minimum Regulated Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolver (16 Bit)</td>
<td>20.00 RPM</td>
</tr>
<tr>
<td>1024 Pulse HTL (Square Wave)</td>
<td>10.00 RPM</td>
</tr>
<tr>
<td>2048 Pulse HTL (Square Wave)</td>
<td>5.00 RPM</td>
</tr>
<tr>
<td>4096 Pulse HTL (Square Wave)</td>
<td>2.50 RPM</td>
</tr>
<tr>
<td>2048 Pulse SIN/COS Encoder (22 Bit)</td>
<td>0.250 RPM</td>
</tr>
<tr>
<td>8192 Pulse SIN/COS Encoder (24 Bit)</td>
<td>0.125 RPM</td>
</tr>
</tbody>
</table>
Alternative System (Gearbox Selection)

Considering the same reference specifications on a drive system with a low ratio single stage gearbox and a 2048 pulse SIN/COS encoder with a gear ratio of 6:1 we determine the following results;

Min Motor Speed at Full roll (RPM) =
    Maximum Web Speed / ((\(\pi \times \text{Core Diameter”} \)) / 12) * Gear Ratio
12.00 fpm / ((\(\pi \times 20” \)) / 12) * 6.00 = \textbf{0.29 RPM}

Max Motor Speed at Core (RPM) =
    Maximum Web Speed / ((\(\pi \times \text{Core Diameter”} \)) / 12) * Gear Ratio
12.00 fpm / ((\(\pi \times 6.75” \)) / 12) * 6.00 = \textbf{40.74 RPM}

Max Motor Speed at Full roll (RPM) =
    Maximum Web Speed / ((\(\pi \times \text{Core Diameter”} \)) / 12) * Gear Ratio
12.00 fpm / ((\(\pi \times 20” \)) / 12) * 6.00 = \textbf{13.75 RPM}
Alternative Solution (Motor Selection)

Motor Selection; Determine the motor torque requirements at core & full roll

Max Torque at Core (in. lbs) =
\[
\left( \frac{\text{Core Diameter}}{2} \right) \times \left( \frac{\text{Maximum Web Tension}}{\text{Gear Ratio} \times \text{Gear Efficiency}} \right) \\
\left( \frac{6.75”}{2} \right) \times \left( \frac{140 \text{ lb.}}{6.0 \times 0.96} \right) = 82.03 \text{ lbf-in}
\]

Max Torque at Full Roll (in. lbs) =
\[
\left( \frac{\text{Full Roll Diameter}}{2} \right) \times \left( \frac{\text{Maximum Web Tension}}{\text{Gear Ratio} \times \text{Gear Efficiency}} \right) \\
\left( \frac{20”}{2} \right) \times \left( \frac{140 \text{ lb.}}{6.0 \times 0.96} \right) = 243.06 \text{ lbf-in}
\]
With these load criteria we can consider a synchronous motor with; the minimum of **82.03 lbf-in** of torque at the maximum speed at core (40.74 RPM) and **243.06 lbf-in** of torque at min speed @ full roll (0.29 RPM).

Based on the data, we select a standard motor rated for;

**(28Nm) 247.82 lbf-in** of stall torque and

**(22.5Nm) 199.15 lbf-in** at 2000RPM.
Active Torque Control Component to Losses

The torque required to produce max tension without considering losses is 233.33 lbf-in.

Giving an active tension control component of:
0.05 * Max Tension Control Requirement = 0.05 * 233.33 lbf-in = 11.67 lbf-in

With friction losses of (243.06 lbf-in – 233.33 lbf-in = 9.73 lbf-in) 9.73 lbf-in
The losses are less than the magnitude of the active tension control component.

This relates to 6/1 * 6.19 lbf-in = 37.17 lbf-in on the output of the gearbox, and 37.17 / 10 in. (full roll radius) = 3.72 lb. of open loop tension disturbance on the web at full roll.

Selecting low ratio gearing with increased motor size offers a drive system with a higher level of inherent accuracy, and control dynamics.

We have gone from a system that had a losses to active tension control component ratio of >40:1 to a system with a ratio of less than one. A system that inherently imparted disturbances of 18.687 lb. of open loop tension disturbance on the web at full roll to a system that offers five times less open loop tension disturbance.
In this example, the motor selected has a rated torque of 247.82 lbf-in. Considering a torque ripple of 2.5%, the ripple at the motor shaft will be:

\[ \sim 0.025 \times 247.82 \text{ lbf-in} = 9.73 \text{ lbf-in} \]

This relates to \( \frac{6.0}{1} \times 9.73 \text{ lbf-in} = 37.17 \text{ lbf-in} \) on the output of the gearbox, and \( \frac{186.875}{10} \text{ in. (full roll radius)} = 3.72 \text{ lb.} \) of open loop tension disturbance on the web at full roll.
Selecting low ratio gearing with increased motor size offers a drive system with a higher level of inherent accuracy, and control dynamics.

We have progressed from a system that had a losses to active tension control component ratio of >40:1 to a system with a ratio of less than one.

A system that inherently imparted disturbances of 18.687 lbs. of open loop tension disturbance on the web at full roll to a system that offers five times less open loop tension disturbance.

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<th>Performance Requirement</th>
<th>Traditional</th>
<th>Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Loss to Max Torque</td>
<td>4.38 lbf-in:2.15 lbf-in</td>
<td>9.73 lbf-in:233.33 lbf-in</td>
</tr>
<tr>
<td>Loss to Active Torque</td>
<td>40.75:1</td>
<td>0.833:1</td>
</tr>
<tr>
<td>Torque Ripple Disturbance @ Web</td>
<td>18.687 lb</td>
<td>3.72 lb</td>
</tr>
</tbody>
</table>
Conclusions

Considering lowest practical gear ratio or if feasible even direct drive for web handling at very low web speeds can enhance machine tension control performance significantly by eliminating the issues of load isolation through friction losses, losses to active tension control component, and torque error magnification.

In systems with lower to moderate power requirements the increased cost of the larger drive system in most cases will be offset by the reduced costs of the system gearing.
Thanks for your Time

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