How Accurately Can I Guide My Web?

by

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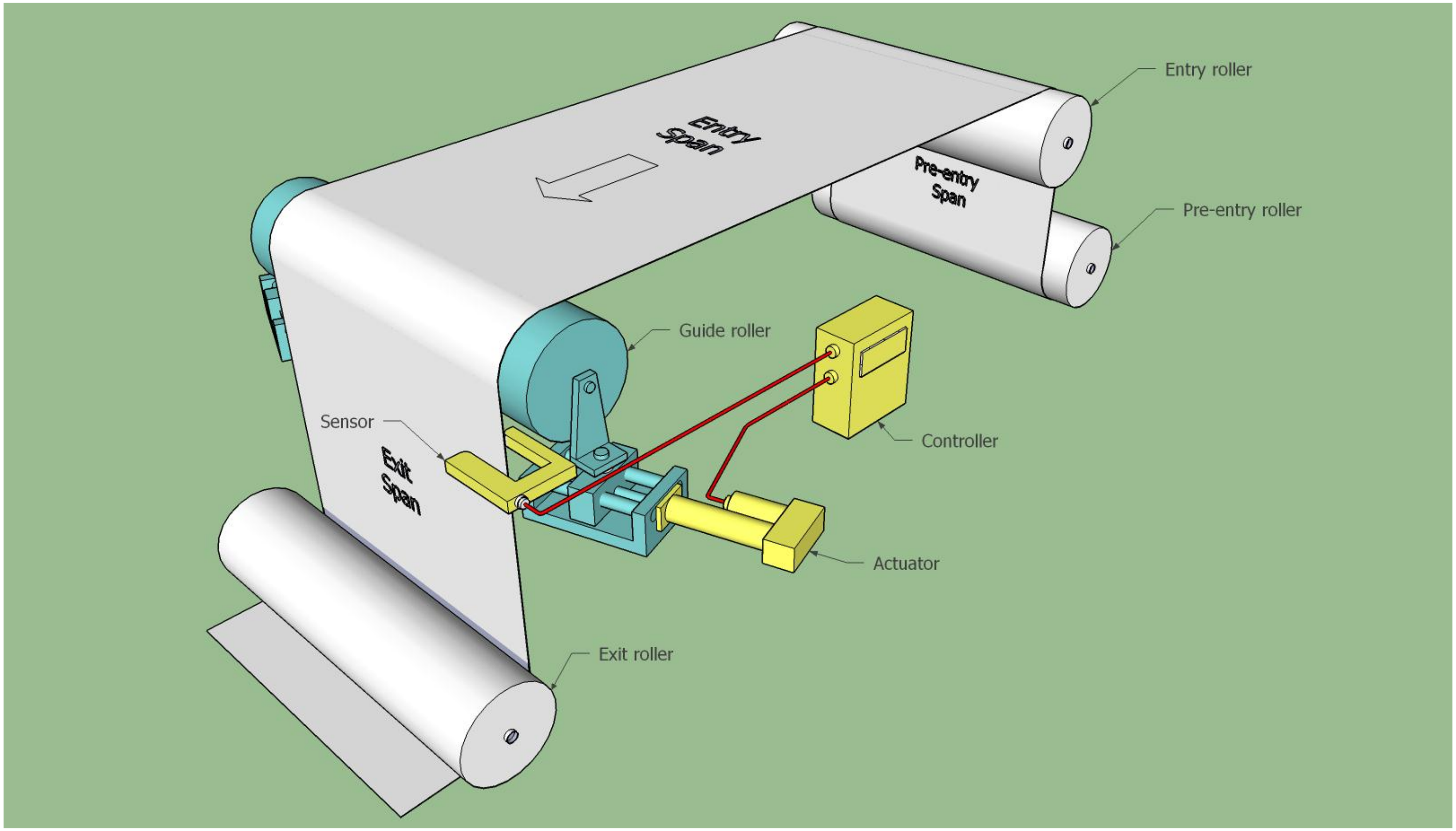
NormalEntry.com

A typical steering system

(Also known as a remote pivot system)



Types of guiding systems

- There are three categories of web guiding systems.
  - Unwind, Rewind & Intermediate
- Due to limitations of time this presentation will deal with two types of intermediate guide.
  - Steering guides like the one in the opening slide.
  - Displacement guides in which both of the rollers of the entry span pivot in tandem.

Components

- Guide roller shifts laterally and pivots at the same time.
- Actuator drives guide roller
  - Motor-driven screw, hydraulic or pneumatic cylinder.
- Sensor detects deviation of web edge or printed registration mark from setpoint
  - May use light, ultrasound or flowing air
- Controller amplifies deviation of sensor signal from setpoint and amplifies it to drive the actuator in a direction that reduces error.

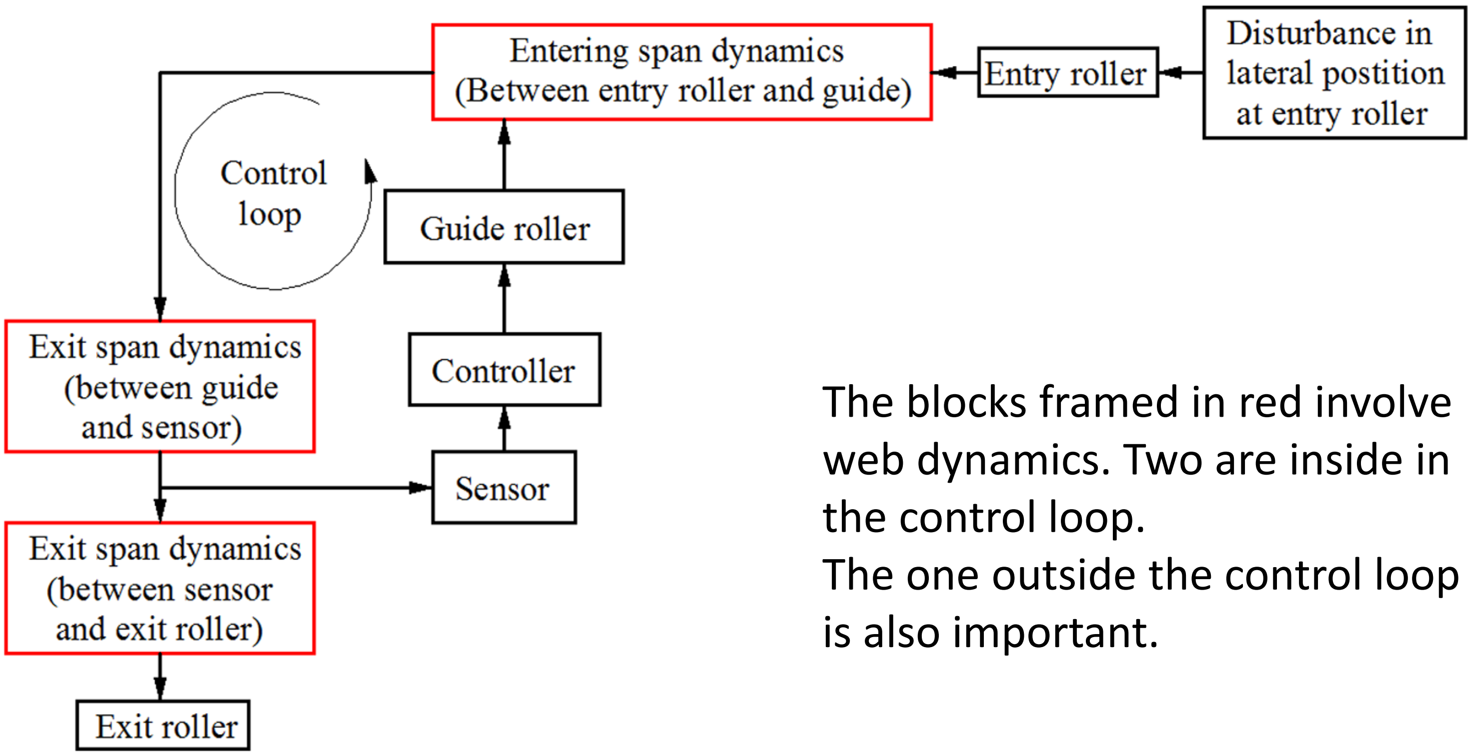
Control

- These are proportional, closed loop systems in which any control action gets modified before it's completed.
  - Analysis of such systems involves challenging mathematics which we won't get into.
  - Animated simulations will be used instead to illustrate their behavior.
  - Focus will be on how web behavior affects results.

Web mechanics play a big role in system performance

- Any change in the web's angle of entry to a roller causes a secondary lateral "tracking" motion on the roller surface.
- The angle of entry is complicated by the fact that a web doesn't behave like a perfectly flexible string.
- When it is shifted laterally at either end, it bends in its own plane like a flexible beam.

Control system block diagram



The blocks framed in red involve web dynamics. Two are inside in the control loop.
The one outside the control loop is also important.

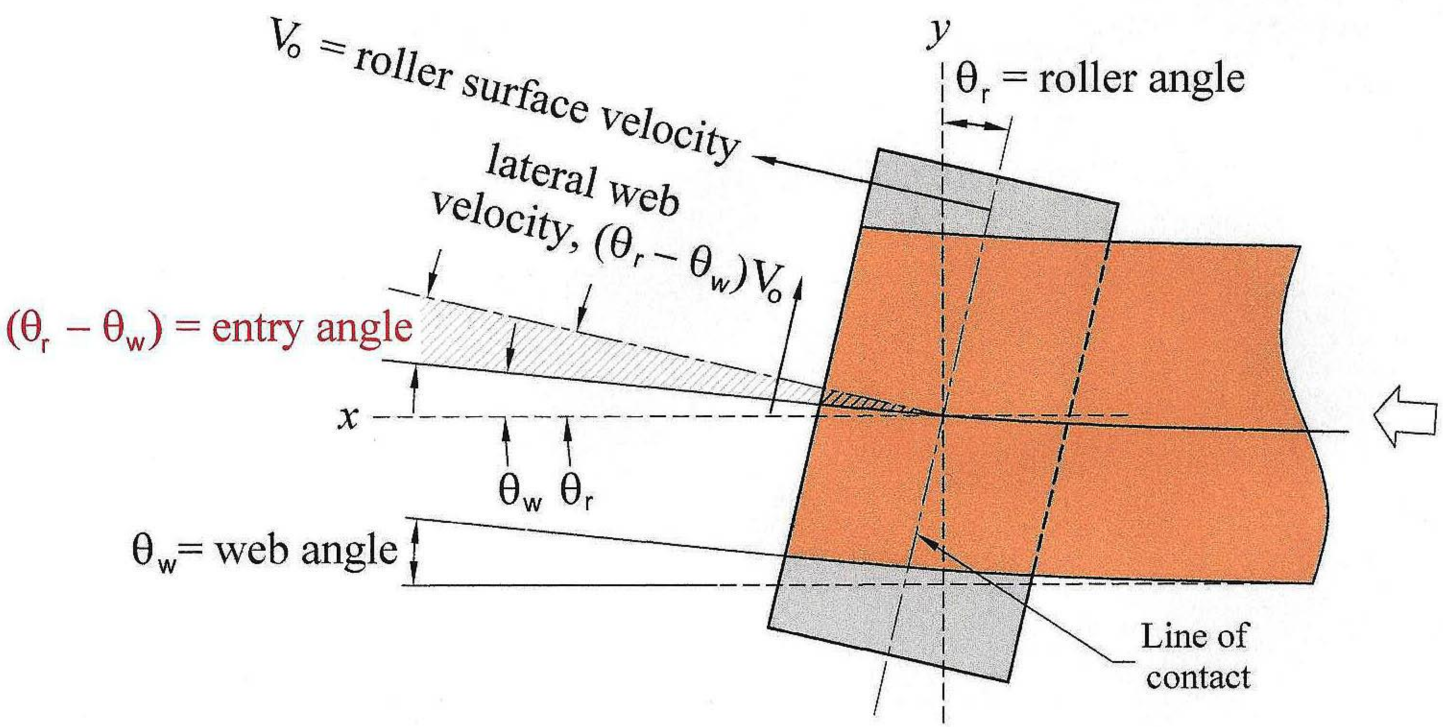
Delays

- Delays cause trouble in control systems.
  - Sensors & controllers are rarely an issue.
  - Actuators unavoidably contribute a significant delay.
    - For example, converting the rotation of a motor to lateral position takes time. Control engineers call this integration delay.
    - By itself, integration delay in the actuator doesn’t prevent high performance control, but it doesn’t leave much room for delays caused by the web.

Lateral motion on rollers

- Webs move with rollers, but they also move “on” them.
- When a web approaches a roller at any angle other than perpendicular to the roller axis, it will track laterally in a direction that takes it back to a perpendicular condition (*normal entry*) and the lateral speed of the motion will be equal to the product of the surface speed of the roller and the entry angle .

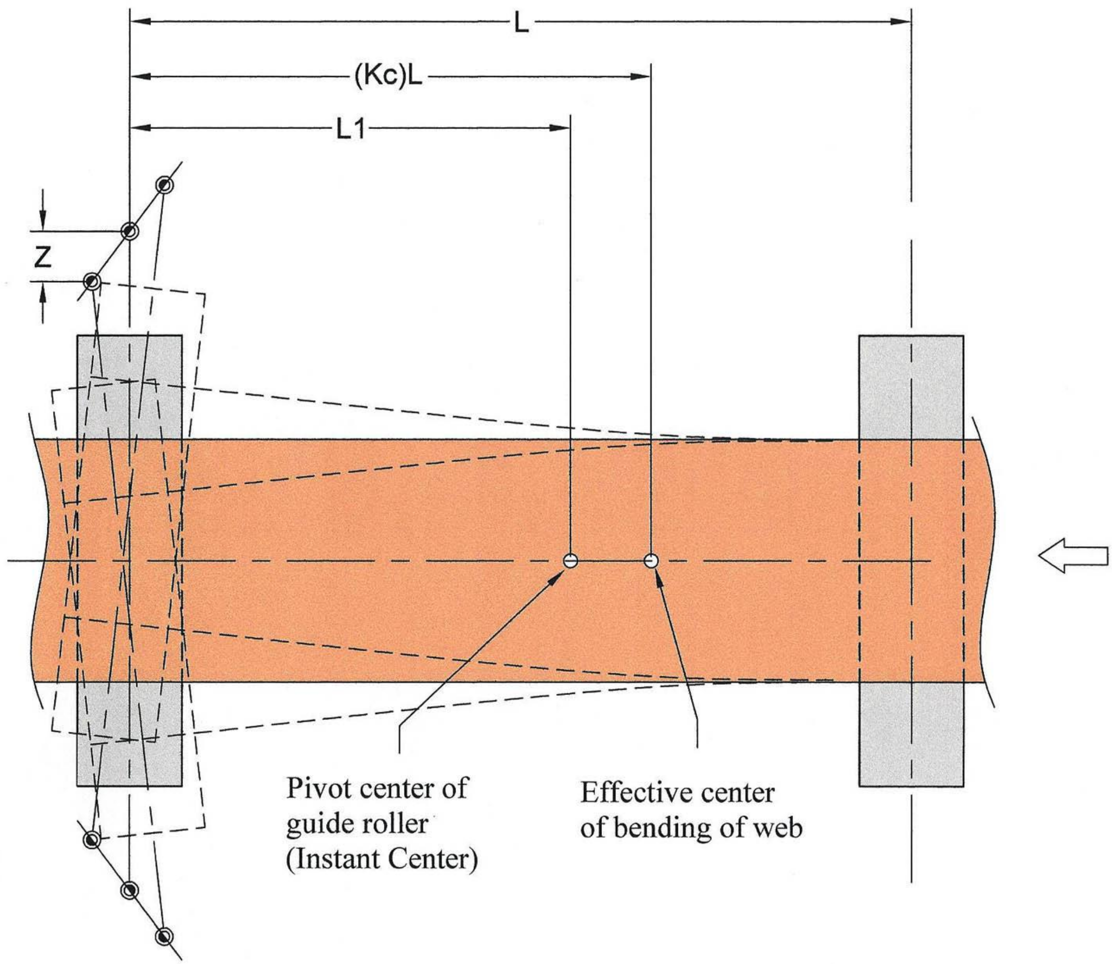
Normal entry



Three sources of lateral motion

- Upstream lateral shift that changes the web angle at the downstream roller.
- A lateral shift of a guide roller.
- Pivoting of a guide roller which changes the roller angle.

Web shape


L
(Kc)L
L1
Z
Pivot center of
guide roller
(Instant Center)
Effective center
of bending of web

Web shape (cont.)

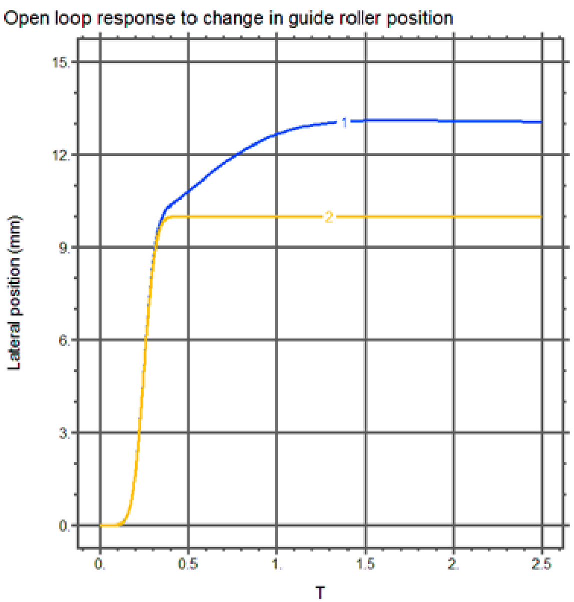
- The dashed lines represent a web after it has settled down following a shift in a guide roller.
- The shape is like that of a cantilevered beam, anchored at the upstream end, but modified by the web tension.
- All of the bending will be near the upstream end. From the perspective of the guide roller it appears to pivot about an upstream point called the bending center.

Web shape (cont.)

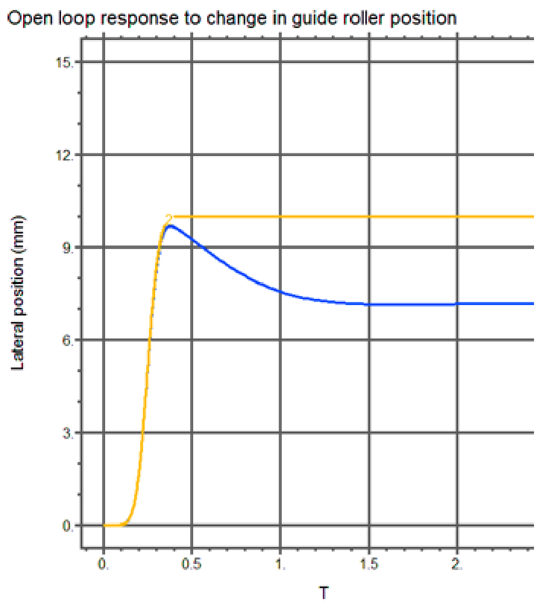
- The distance of the bending center from the guide roller is (*Kc*)L where *Kc* is a coefficient called the curvature factor.
- *Kc* ranges from2/3 to 1.
- For typical applications it will be closer to 2/3. High tension or low bending stiffness will cause it to increase towards 1.0.
- When the web is not in a steady state, for example immediately following a change in upstream position, the downstream end won’t be normal to the roller axis and the shape can become much more complicated.

Dynamics of the entry span

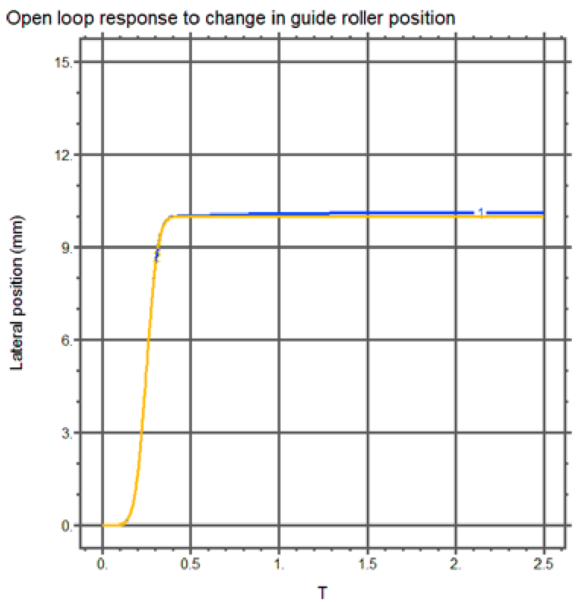
Response to guide roller position



Oversteering
L1 < (Kc)L



Understeering
L1 > (Kc)L

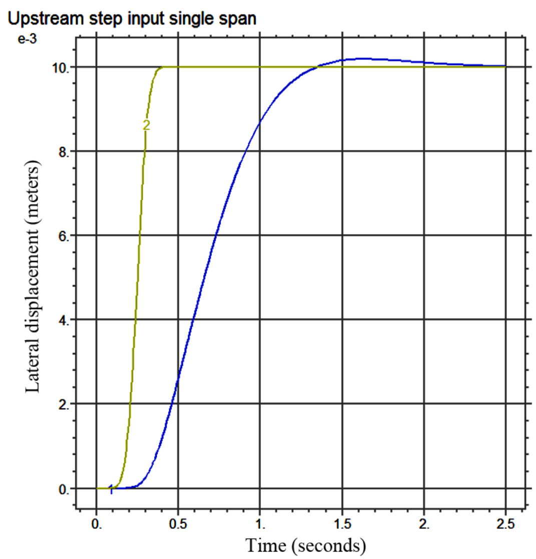


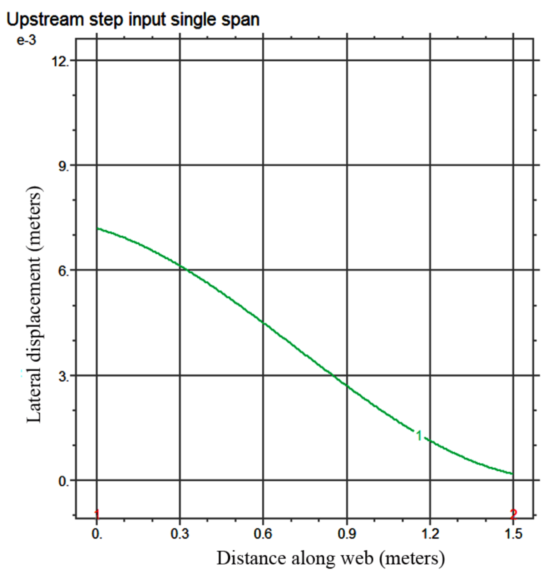
Neutralsteering
L1 = (Kc)L

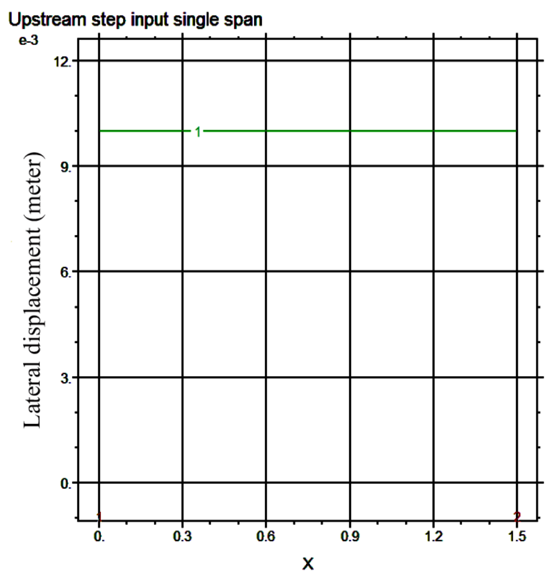
Imagine that the guide roller is manually jogged 1 cm while the web is running and the control system is turned off. Yellow curve is the actuator input. Blue is the web position.

Dynamics of the entry span

Response between parallel rollers to upstream disturbance







Time history of response
Yellow – step input
Blue – position at exit roller

Lateral position along web at 0.28 sec

Lateral position along web at 2.5 sec

When the web is changing position its shape gets complicated. When it finally reaches a steady state it is perpendicular to both roller axes.

Location of the sensor

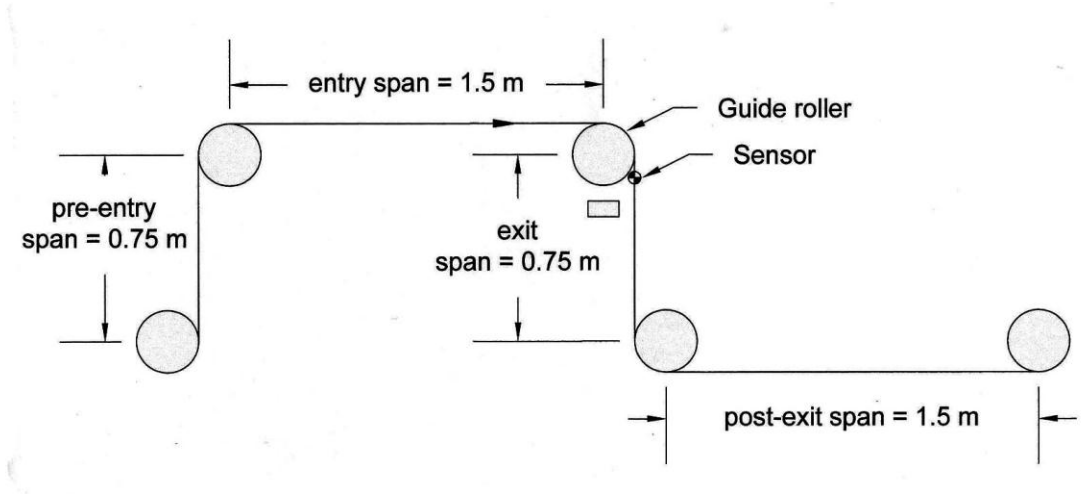
- The natural location of the guide sensor is the exit span immediately following the guide roller because that is where the full effect of the guide roller is first seen.
- If the guide roller pivots in the plane of the entry span and has 90 degrees of wrap, the exit span will behave as though it is running between a pair of parallel rollers because it sees no in-plane angular misalignment from the guide roller.

Location of the sensor (cont.)

- When the sensor is close to the guide roller, it sees the immediate effect of its lateral motion.
- When it is close to the exit roller most of the motion it sees is from the relatively slow tracking caused by the normal entry effect and, as seen from the last slide, this motion is delayed relative to that at the guide roller.
- If the sensor is very close to the exit roller, the sum of all the delays in the control loop usually increases to a point where the system is no longer stable.

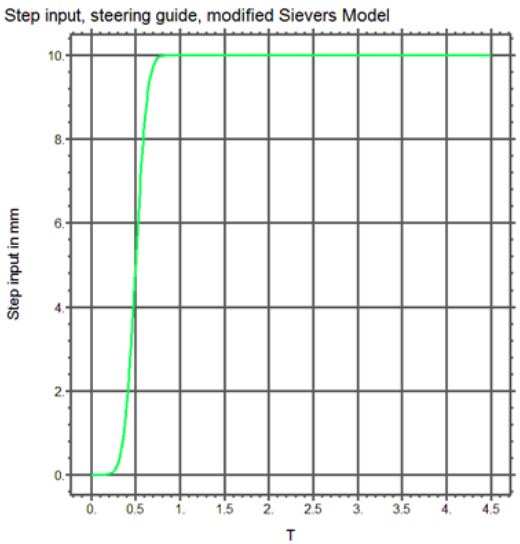
Simulation of steering guide

All of the simulations in this paper are based on the following parameters.

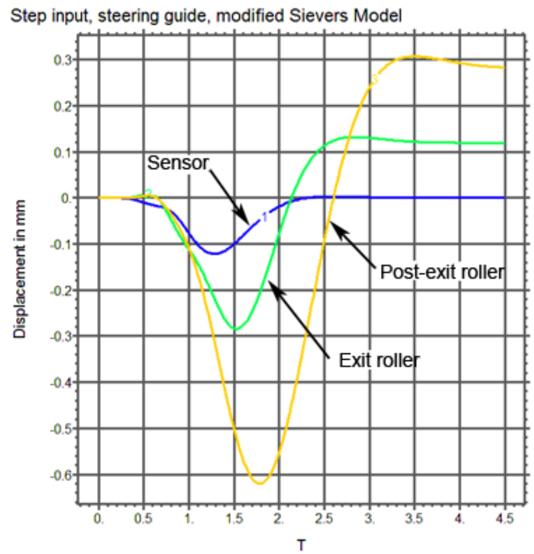


Width = 0.75 m	Tension = 1.75 N/cm	Kc = 0.71
Thickness = 0.025 mm	Poisson's ratio = 0.3	
Modulus = 1.38 GPa	Line speed = 2.m m/s	

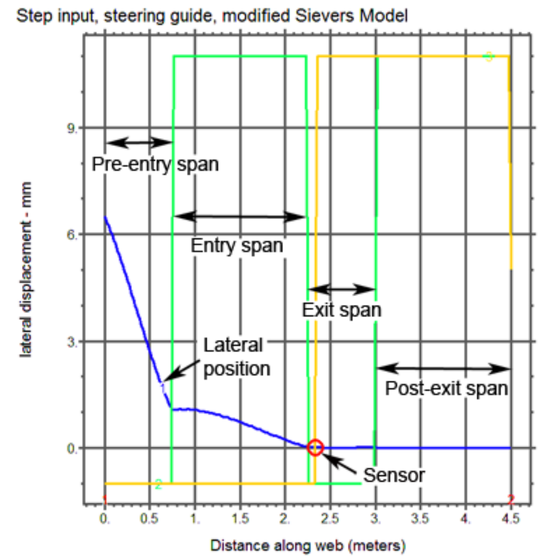
Simulation of steering guide (cont.)



(a) Step input vs time



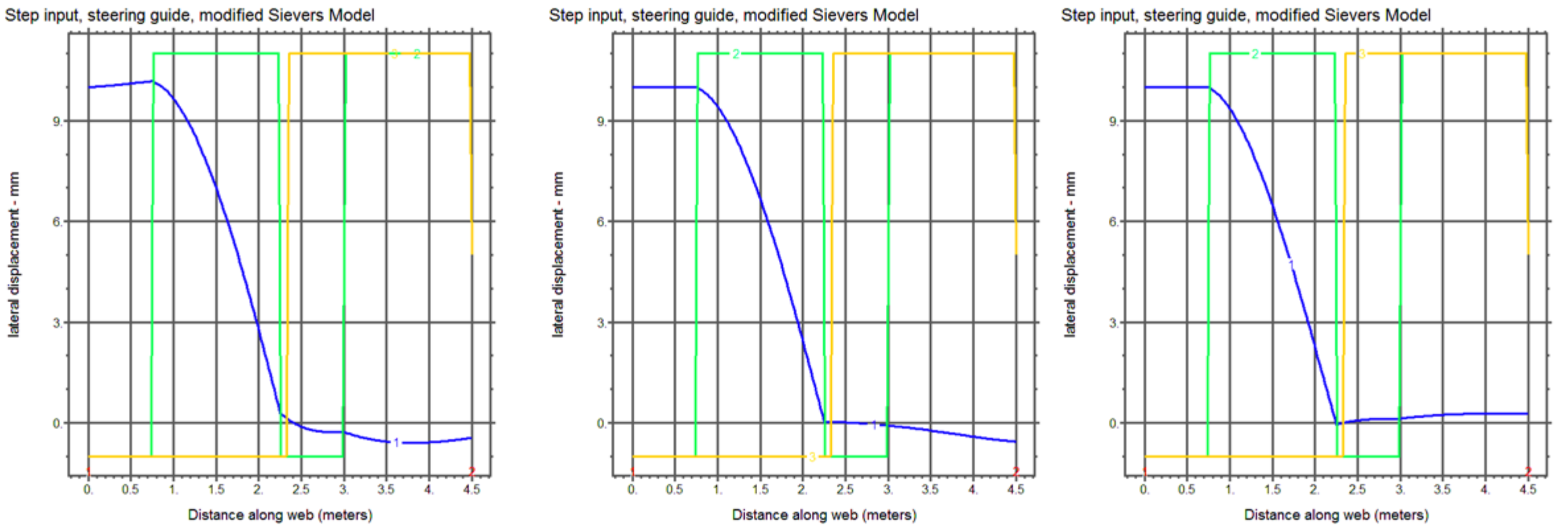
(b) Position vs time at sensor, exit roller and post-exit roller



(c) Lateral position Vs distance along web at 0.54 sec

In the (c) the vertical green bars mark the limits of each span. The yellow one marks the sensor location.

Simulation of a steering guide (cont.)



(d) At 1.44 sec

(e) At 1.98 sec

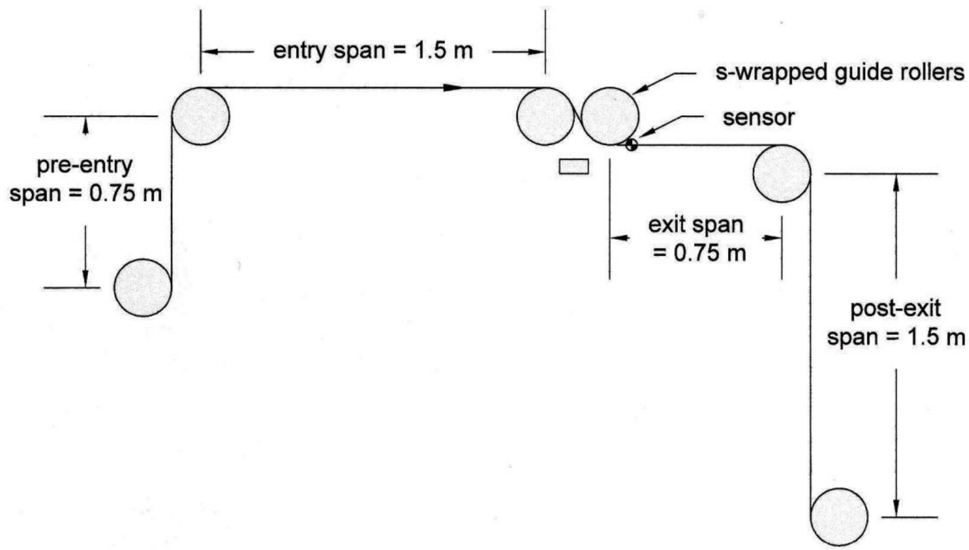
(f) At 4.5 sec

In (f) the web has settled into its steady state. At the sensor, the error is zero, but at the exit roller there is a residual offset of 0.12 mm (0.005 inch) and at the post-exit roller there is a larger offset of 0.28 mm (0.011 inch). Note the non-zero offsets at 1.44 & 1.98 sec – more about this later.

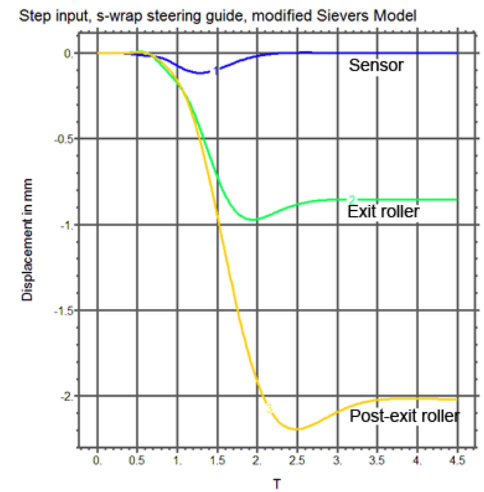
Simulation of a steering guide (cont.)

- In the graphs of the previous slide, the web appears to make an abrupt change in slope at the guide roller.
- Small changes in slope can occur across rollers because of shear, as at the exit roller in (d). However, the change at the guide roller is caused by the fact that the graph is a flattened representation of a 3D geometry.
- The 90 degree wrap of the guide roller changes the direction of the web, which had been oblique to the machine direction, into alignment with it in the exit span.
- Although this makes for a problem in interpreting the graph, it has real benefit to the guiding system because it converts the in-plane angular misalignment of the entry span into out-of-plane twisting in the exit span.

The exit span can undo the guiding



(a) Passline

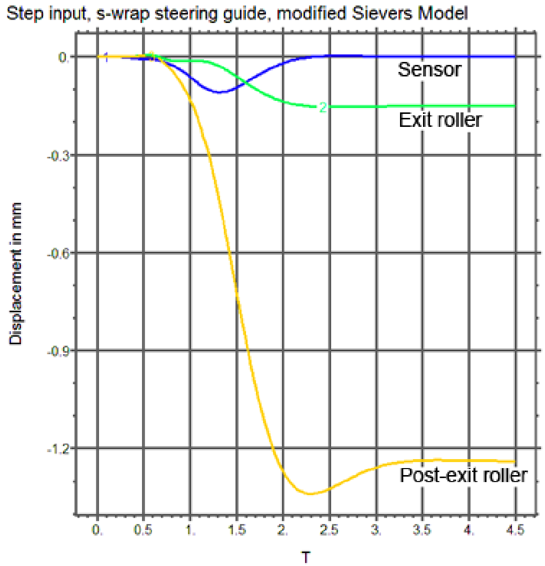


(b) Lateral errors
Vs time

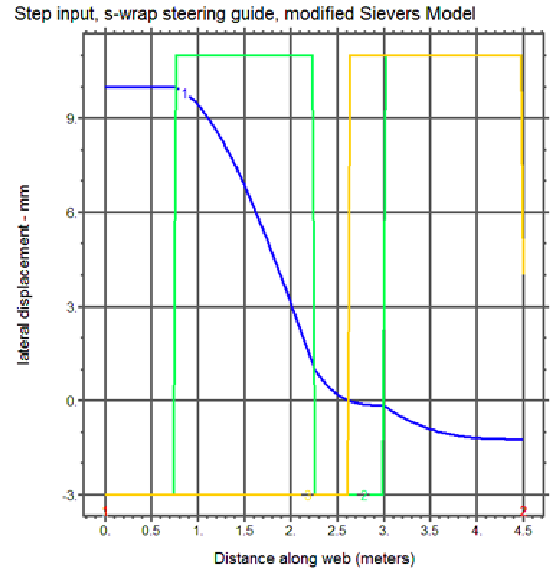
When the exit span is in the same plane as the entry span, large errors appear downstream because the pivoting of the guide roller alters the in-plane angle of the upstream end of the exit span. This produces steering action that causes a steady state error at the post-exit roller (2.0 mm for a 2 cm disturbance at the pre-entry roller).

The exit span can undo the guiding

(Cont.)



(a) Time response with sensor half way down the exit span



(b) Steady state lateral position with sensor half way down the exit span

Moving the sensor closer to the exit roller reduces the error at the expense of stability. Putting it half way down reduces the error at the post-exit roller to 1.2 mm. The seriousness of the loss in stability will depend on the quality of the guiding system.

Weave regeneration

- First reported and analyzed by Lisa Sievers in her 1987 thesis.
- Her work was sponsored by Kodak. Apparently someone there had noticed that when a web guide was used to correct a slowly weaving error (in Sievers' experiments a back & forth oscillation of 0.033 to 0.067 cycles/second), it would reappear downstream of the sensor.
- The problem was similar to the one just described. However, instead of being caused by the pivoting of the guide roller, it was caused by changes in the angular orientation of the web on the roller.

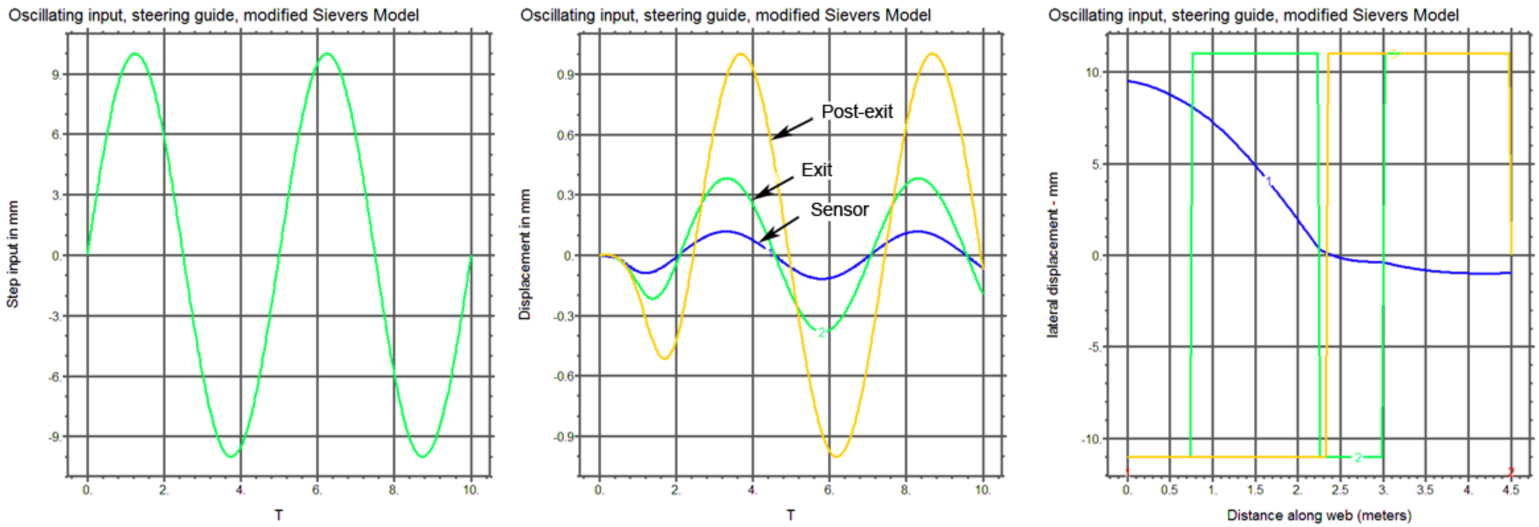
Weave regeneration (Cont.)

- As the system responded to an oscillating upstream error, the angle between the web and the guide roller axis would weave in and out of a perpendicular relationship.
- This angular variation, unseen as it passed through the sensor, would be passed through to the downstream end of the exit span where it altered the entry angle there and caused tracking motion, thus regenerating the lateral error.
- The variation could then pass in the same manner to the subsequent spans.

Weave regeneration (Cont.)

- Sievers constructed a lab machine that exhibited this behavior and developed a multi-span mathematical model which accurately reproduced it.
- I have implemented an improved version of her model in FlexPDE (an FEA software tool for modeling differential equations) and used it to do all the simulations for this paper.

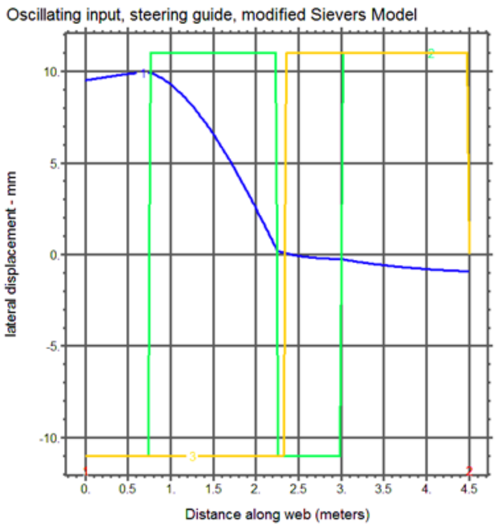
Wave regeneration (Cont.)



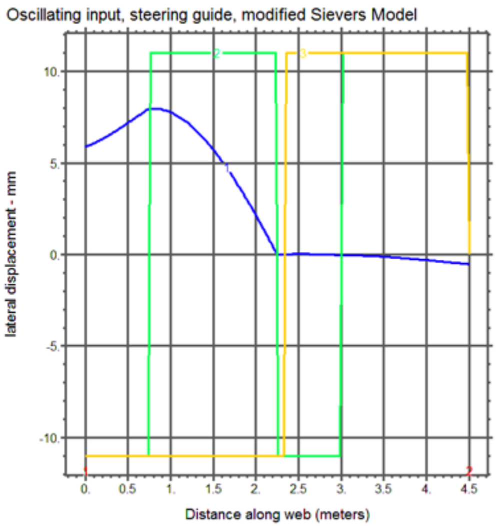
(a) Oscillating input (b) Time response (c) Lateral position at 6 sec

This is illustrated above with a 1 cm, 0.2 cycle/sec oscillatory input. Peak error at the sensor is 0.1 mm (0.004 inch). At the exit roller it is 0.4 mm (0.016 inch) and at the post-exit roller it is 1.0 mm (0.040 inch). Increasing the accuracy of the guide system won't help because it can't control the slope at the sensor.

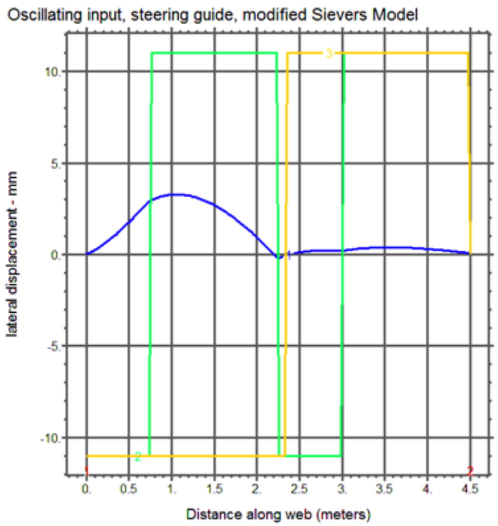
Weave regeneration (Cont.)



(d) Lateral position
at 6.5 sec

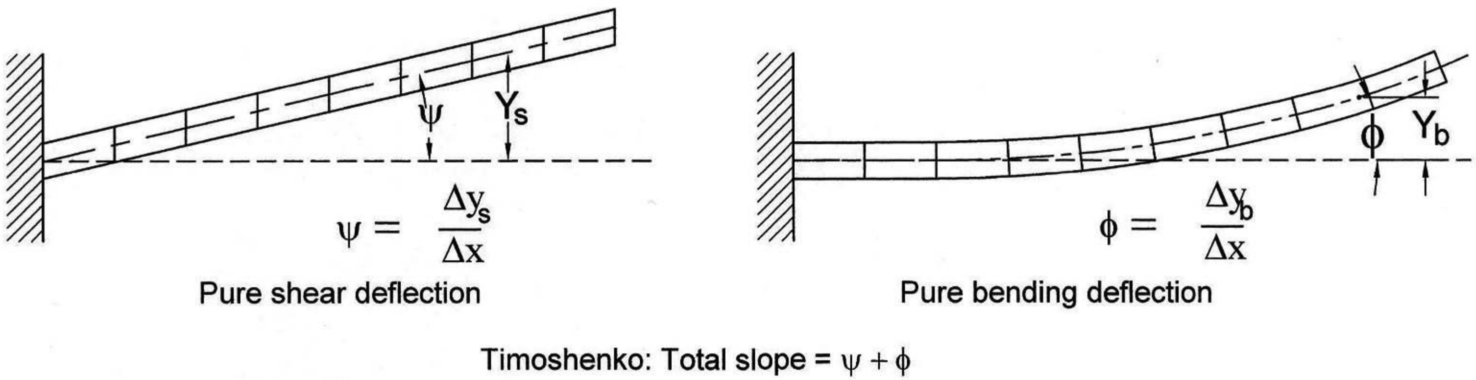


(e) Lateral position
at 7.0 sec



(f) Lateral position
at 7.5 sec

Shear deformation

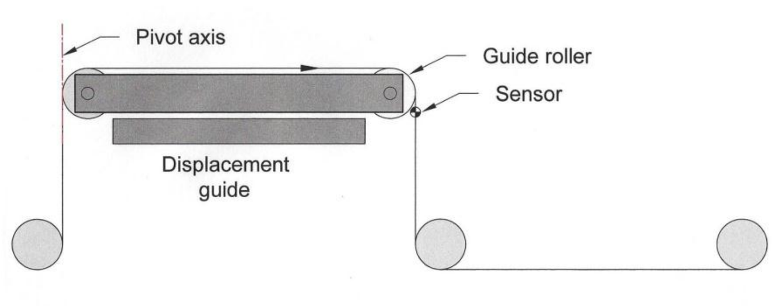


Sievers developed two models. One used a simplified beam model (the Euler-Bernoulli beam) which includes only bending stress. The other used Timoshenko beam theory, which includes the effect of shear. Shear is important. Without it, the steady state error, visible in the step response of the steering guide would not be seen. Furthermore, the Euler-Bernoulli model underestimates the error amplitude of oscillating disturbances. For example, the amplitude of the weave error just presented would b 0.7 instead of 1.0 mm.

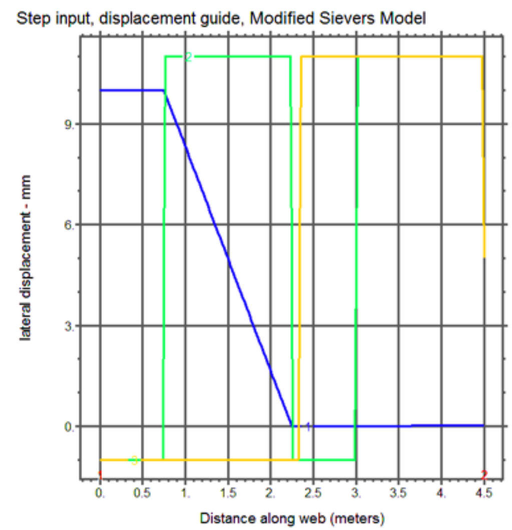
The Timoshenko model is used for all the simulations in this paper.

The displacement guide

Champion of intermediate guides



Passline for displacement guide



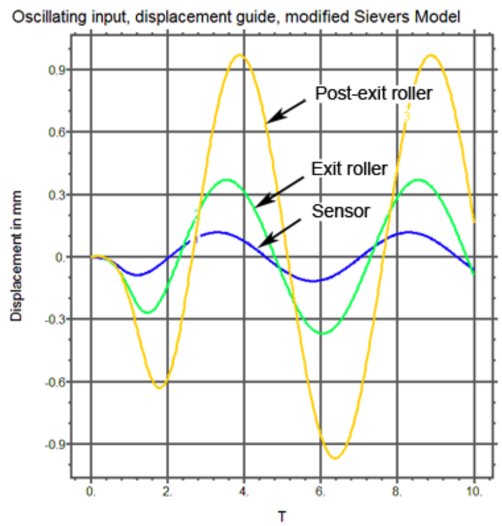
Steady state response to a step input

The system shown above is the same as for the steering guide described earlier except that the rollers are mounted on a frame so they pivot in tandem about the indicated axis. It has a number of advantages.

The displacement guide (cont.)

- In the steady state, there is no downstream regeneration of a step error. This is due to the fact that there is no lateral deformation in the entry span, as can be seen in the previous slide. The web is rotated as though it is a rigid body.
- Overall deformation of the web is minimized. The out-of-plane twisting of the pre-entry and exit spans produces very little stress compared to the in-plane bending of a steering guide. Furthermore, the twisting is symmetrical, so it can't create regeneration issues.
- Dynamics are simplified because steering is always neutral (no over or under steering).
- In the steady state, no lateral traction is needed to keep the web in position on the guide roller because of the absence of lateral deformation in the entry span.

The displacement guide (Cont.)



Displacement guide response to oscillating input

Response to an oscillating input is very similar to that of a steering guide because the transient response (when the web is not in a perpendicular relationship with the axes of the guide rollers) is similar.

Caveats

All mathematical models are based on approximations and assumptions and should be used with caution.

- Other than the normal entry law, no account is taken of web behavior on rollers and there is much that we still don't know about this area – particularly lateral microslip.
- Perfect web traction on rollers is assumed at all times and no attention has yet been given to traction requirements during transient conditions.
- Sievers' tests on the Timoshenko model were successful, but they were limited to weave frequencies of 0.017 to 0.067 Hz on one web material.

Caveats (Cont.)

No attention has been given to any of the advanced control systems which are currently emerging (reported at IWEB and in the literature). These have the potential to make considerable improvements in the capabilities of commercially available systems.

- Seshradi, A., Pagilla, P. R., “Optimal Web Guiding”, Journal of Dynamic Systems, Measurement, and Control, January 2010, Vol. 132
- Seshradi, A., Pagilla, P. R., “Adaptive Control of Web Guides”, 18^{th} IFAC World Congress, August 2011

Things we’re sure of

Many of the guidelines mentioned in this paper are supported well by field experience.

- Using 90 degrees of wrap between the entry and exit spans of a steering guide with the plane of the guide roller pivoting in the plane of the entry span.
- Reduction in system stability as the sensor is moved down the exit span (never put it in the post-exit span).
- Steady state offset error when the entry and exit spans are not at 90 degrees.
- Shelton’s steady state beam model (including shear) is supported well by experiments described in his thesis.
- The advantages of a displacement guide.

The future

- Once installed, customers expect web guiding systems to operate without attention. Since web dynamics change considerably with variations in materials and line speed, the reigning paradigm for vendors has been to keep the control system simple and use good application techniques to avoid web dynamics.
- However, new applications such as printed electronics require higher accuracy and are putting pressure on this approach. Powerful imbedded computers and better web models make it possible to apply advanced control techniques which automatically adapt to line and web properties without placing additional demands on the customer. Systems like this are currently emerging (reported at IWEB and in the literature) and have the potential to make considerable improvements in the capabilities of available systems.
  - Seshradi, A., Pagilla, P. R., “Optimal Web Guiding”, Journal of Dynamic Systems, Measurement, and Control, January 2010, Vol. 132
  - Seshradi, A., Pagilla, P. R., “Adaptive Control of Web Guides”, 18th IFAC World Congress, August 2011