How Accurately Can I Guide My Web?

Presented at 2015 AIMCAL Web Coating & Handling Conference

By Jerry Brown
Essex Systems

It's very hard to get a precise answer to this question. The reason is not that vendors are secretive. The only honest answer is that, "It depends on lots of things and many of them are outside the control of the vendor." This paper provides insight into some of these factors and suggests ways to optimize results.

A typical web guiding system

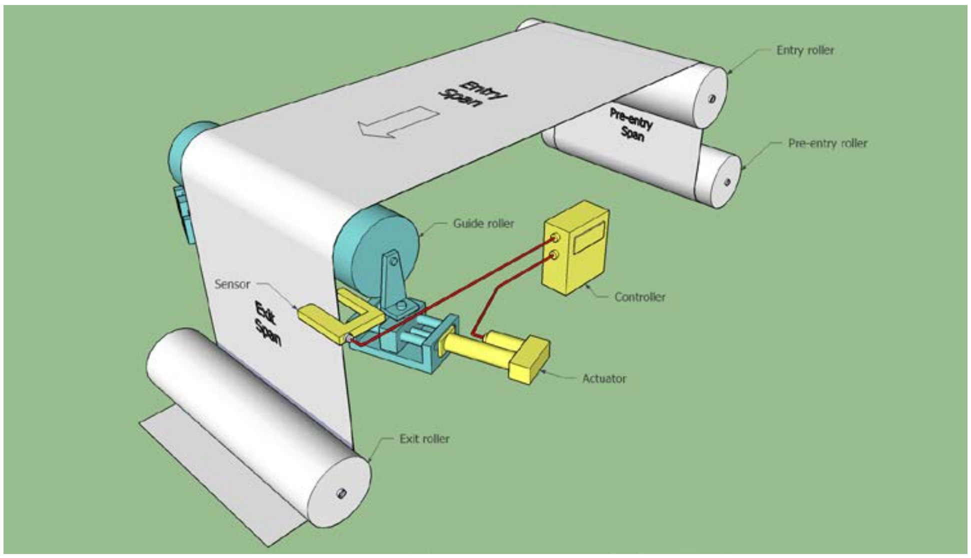


Figure 1
A typical web guiding system
Remote pivot type (also known as a steering guide)

Figure 1 shows a typical steering guide system. The roller at the end of the entry span shifts laterally and pivots at the same time. It is driven by an actuator which in this case is a motor-driven screw. It could also be driven by a hydraulic cylinder (which requires the addition of a hydraulic power unit and servo valve) or a pneumatic cylinder (which uses shop air and a servo valve). There is a sensor which detects any deviation in the web edge from the desired set point. It may use, light, ultrasonic energy or flowing air. Deviation in the web edge position is amplified in the controller and used to drive the actuator in a direction that reduces the error. This sounds simple, but it's complicated by the following factors.

1. It's a proportional, closed-loop control system in which any corrective action gets modified before it's completed. Analysis of such systems involves some challenging mathematics (which we won't get into).
2. Complex web behavior is part of the control system
    a. When the web is shifted laterally by either a guide roller or by an upstream disturbance, the entry angle onto the guide roller is changed and this causes a secondary lateral "tracking" motion relative to the roller surface.
    b. The web doesn't behave like a perfectly flexible string. When it shifts laterally at either end, it bends in its own plane like an elastic beam.

There are three basic categories of guiding systems – unwind, rewind and intermediate. Due to limitations of time, this paper will focus on two types of intermediate system. One is the steering system shown in Figure 1 and the other, known as a displacement guide, is similar except that the upstream roller of the entry span pivots in tandem with the guide roller. Once you understand these, it is relatively easy to understand unwind and rewind guiding.

Control system dynamics

When viewed as a block diagram, a steering guide system of Figure 1 looks like this,

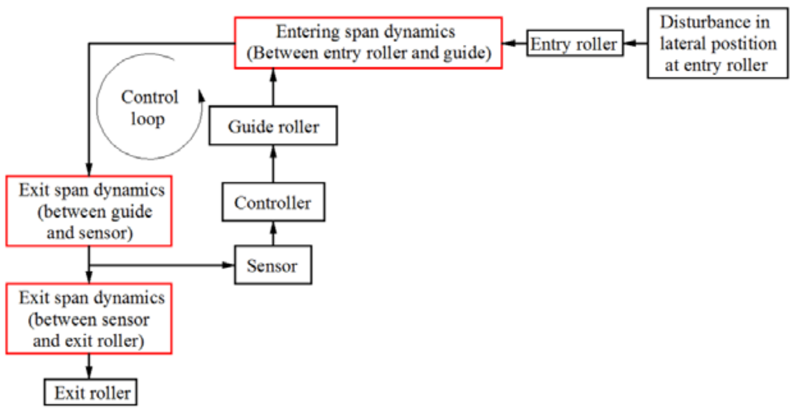


Figure 2
Block diagram of steering guide of Figure 1

The blocks framed in red involve web dynamics. Note that two of them are in the control loop. There is a third block outside the control loop, which as we will see later, can be very important.

The word “dynamics” can mean many things. In the case of a typical web guide, though, it most often implies a time delay and time delays are almost always problematic in control systems. Of the components supplied by vendors, sensors and controllers are rarely an issue in this regard. However, the actuator always contributes an unavoidable delay. For example, a motorized screw cannot instantaneously shove a guide roller from one position to another. Converting the rotational velocity of the motor to lateral position takes time. The same thing is true for converting flow to position in a hydraulic or pneumatic actuator. Control engineers call this integration delay. It doesn’t necessarily prevent high performance guiding, but it doesn’t leave much room for additional delays. Fortunately for web guiding, delays caused by entry and exit span dynamics can be reduced to low levels by careful application engineering.

Lateral motion on rollers (normal entry effect)

Webs move with rollers, but they also move “on” them.

When a roller shifts laterally, it is obvious that the web must move with it, but the web can also “track” laterally on the roller surface. When the web approaches the roller at any angle other than perpendicular to the roller axis, it will track laterally in a direction that reduces the angle (taking it toward perpendicular *or 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.

So, in a span that includes a steering guide there can be three sources of lateral motion.

1. An upstream lateral disturbance which changes the web angle at the guide roller.
2. A lateral shift of the guide roller which carries the web with it.
3. Pivoting of the guide roller which changes the roller angle.

Items 2 and 3 are usually driven simultaneously by the same actuator.

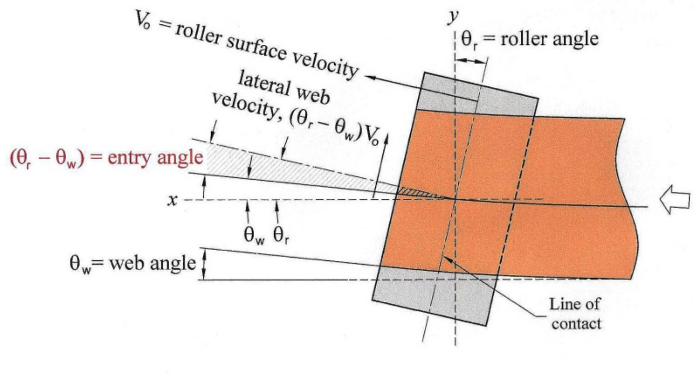


Figure 3
Entry angle (function of both roller angle and web angle)

So long as there is adequate traction to prevent slipping, the normal entry effect is a dominant influence in lateral behavior. It causes the web to move laterally relative to the roller with a velocity equal to $(\theta - \psi)V_o$ and that velocity will change as either θ_r , θ_w or V_o change. The other big influence on lateral behavior is web shape because it controls θ_w.

Web shape

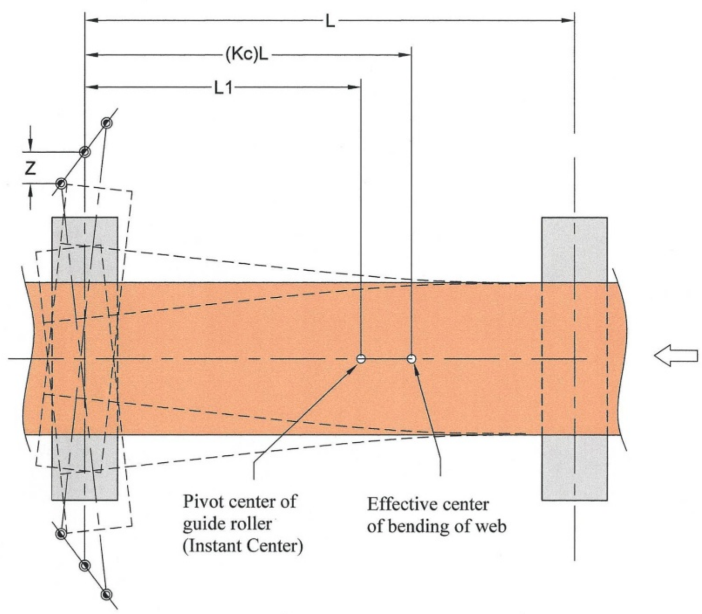


Figure 4
Web curvature (steady state response to roller misalignment)

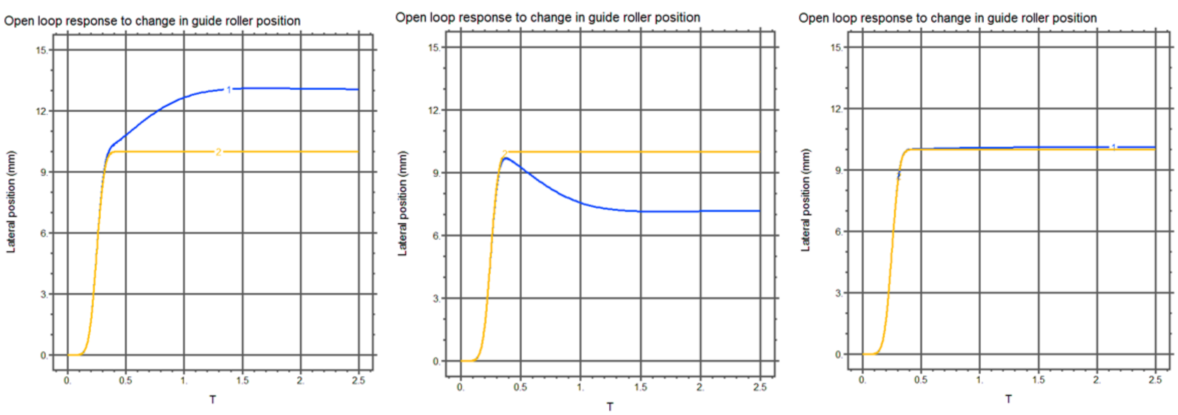
As mentioned earlier, the web doesn't behave like a perfectly flexible string. When it shifts laterally at either end, it bends in its own plane like an elastic beam [1]. In Figure 4**,** the dashed lines represent a web after it has settled down, following a shift in the guide roller. The shape is similar to a cantilevered beam, anchored at the upstream end, but modified by the web tension. At the downstream end, the normal entry effect causes the web to become perpendicular to the misaligned roller axis. All of the bending will be at the upstream end; so at the point where the web enters onto the guide roller, it is straight and angled as though it has pivoted about an upstream point called the "bending center". The distance of the bending center from the guide roller is equal to $(K_c)L$ where K_c is a coefficient called the curvature factor and L is the length of the span. K_c ranges from 2/3 to 1.0. For typical plastic film applications, it will be closer to 2/3. High tension or low bending stiffness will cause it increase toward 1.0.

When the web is not in a steady state, for example, immediately following a change in the upstream position; the downstream end won't be normal to the roller axis and the shape can become much more complicated during the time the web is moving laterally.

Dynamics of the entry span

Response due to a change in guide roller position

Imagine that the guide roller is manually jogged 1.0 cm while the web is running and the control system is turned off (open loop). If the instant center distance, L_1 is less than the bending center distance $(K_c)L$, the web will be "oversteered". This means that the change in roller angle which accompanies the lateral motion of the roller will be too great and the web will have to track forward from its initial position to achieve normal entry. If the instant center distance is greater than the bending center distance, the web will be "understeered", meaning that the change in roller angle will be too small and the web will have to track backward from its initial lateral position to achieve normal entry. The optimum situation for a guiding system is when the instant center and bending center coincide. This is known as neutral steering. The graphs in Figure 5 are time plots that illustrate these three situations. There are two curves in each plot. The yellow one is the lateral position of the guide roller (the input). The blue curve shows the lateral position of the web at the exit of the guide roller (which includes the tracking motion on the roller surface). In the case of neutral steering, the curves overlap so that only the blue one is visible.



(a) oversteering (b) understeering (c) neutralsteering

Figure 5
Step response to guide roller position

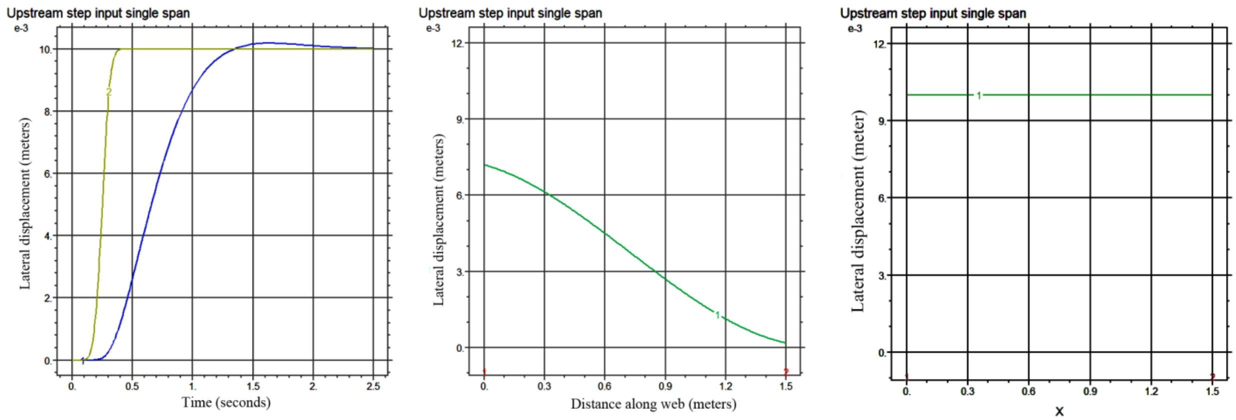
Although the steering geometry influences entry span dynamics, it does not have a large influence on the dynamic performance of a guiding system provided that L_1 is kept between $(2/3)L$ and L.

Parameters for simulations are:

Entry span length 1500 mm	Modulus 1.38x10^9 Pa	Line speed 2.5 m/s
Width 750 mm	Tension 1.75 N/cm	K_c = 0.71
Thickness 0.025 mm	Poisson's ratio 0.3	

Table 1
Material parameters for simulations

Response between fixed parallel rollers due to a change in upstream position



(a) Time response (b) Shape 0.28 sec (c) Shape at 2.5 sec

Figure 6
Response between parallel fixed rollers to
a lateral upstream displacement

A lateral displacement (yellow curve in Figure 6 (a)) at the upstream end of a span between fixed rollers will initially change the entry angle downstream. The web will track laterally on the downstream roller until the two ends are aligned and the web is straight again. The blue curve in Figure 6 (a) shows the time response at the downstream end.

Figure 6 (b) shows a snapshot of the web shape, 0.28 second after it begins to respond to the input. Note that it is curved at both ends. This is typical of times when it is moving laterally. Figure 6 (c) shows the web shape when it has reached its final lateral position.

Location of the sensor in a guiding system

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. The distance of the sensor from the guide roller, relative to the overall length of the span, has a big effect on stability of the system.

In a steering system like that of Figure 1, the exit span will respond to changes in lateral position at the guide roller in much the same way as for an upstream displacement between parallel rollers shown in Figure 6. When the sensor is close to the guide roller, it sees the immediate effect of its lateral motion; but as it is moved close to the exit roller, it sees less of the immediate effect and more of the relatively slow lateral motion caused by the angle change at the exit roller. If the sensor is very close to the exit roller, the sum of all of the time delays in the system will usually increase to a point where the control system is no longer stable. Therefore, it is important to locate the sensor close to the guide roller.

Simulations of steering guide systems

All of the simulations in this paper are based on the material parameters of Table 1 and will include a web guide with performance parameters typical of a good electromechanical system using optical or ultrasonic sensing.

In the system of Figure 7, the sensor is 1/8 of the way down the exit span.

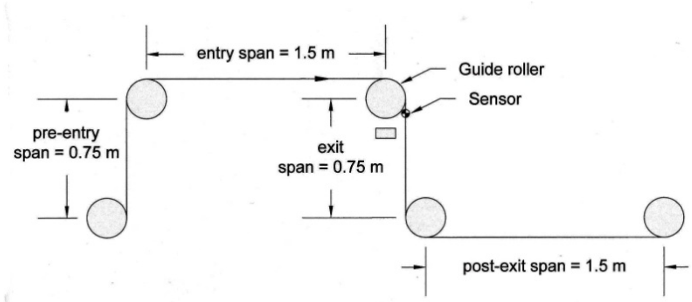
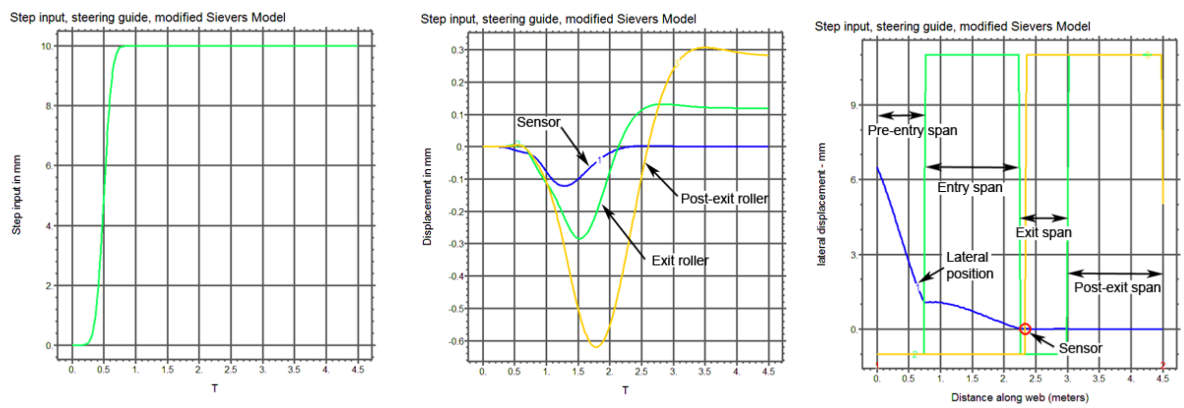


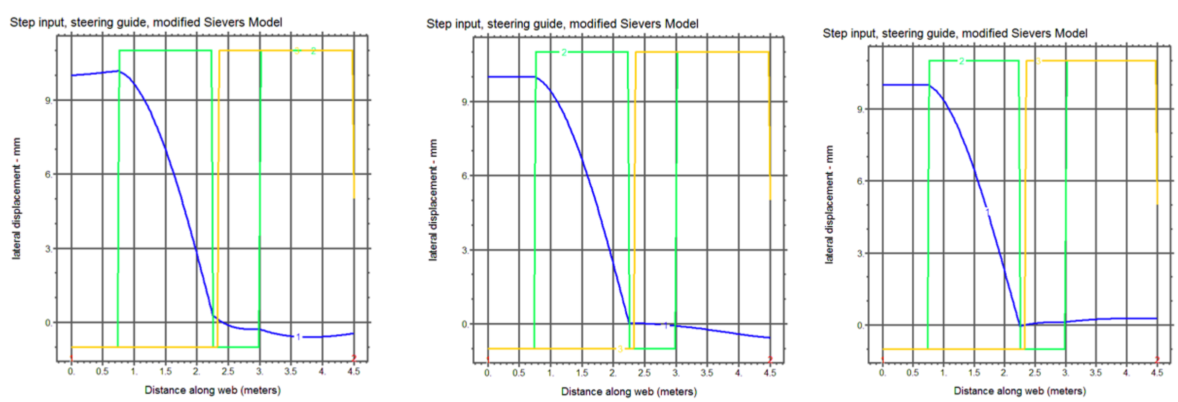
Figure 7
Simulation web path
All rollers other than the guide roller are fixed

The simulation produces an animated image of the lateral position at each instant of time throughout the web path of Figure 7. The direction of travel through the machine is from left to right.

The simulation shown in Figure 8 is for a 1 cm step input shown in (a). The input is applied at the entry to the pre-entry span. A snapshot of the output is shown in (c). It is taken at 0.54 second. The vertical green bars in (b) define the limits of each span. The yellow one marks the sensor location. The violet curve is the lateral position of the web.



(a) Input disturbance (b) Time history of position (c) Lateral position at 0.54 sec



(d) At 1.44 sec (e) At 1.98 sec (f) At 4.5 sec

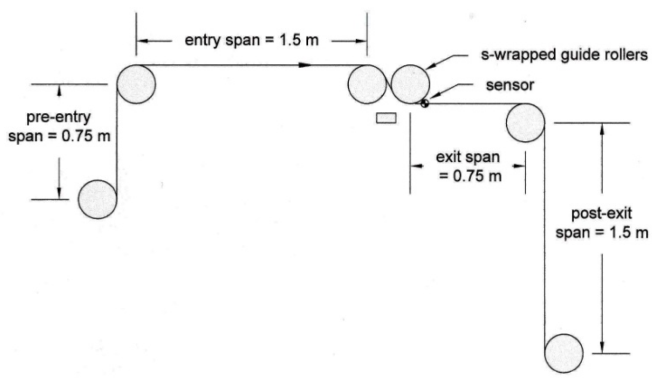
Figure 8
Response to a step input at 0.54, 1.41, 1.98 and 4.5 seconds

In graph (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). These errors are due to shear deformation in the entry span. At the entry side of the guide roller the normal entry effect keeps the web perpendicular to the roller axis (when it's in a steady state), but when it exits the roller there is no normal entry effect to control its angle and the shear deformation causes the web to leave at a small angle off perpendicular. Although the angle is small, it is enough to cause the downstream offsets.

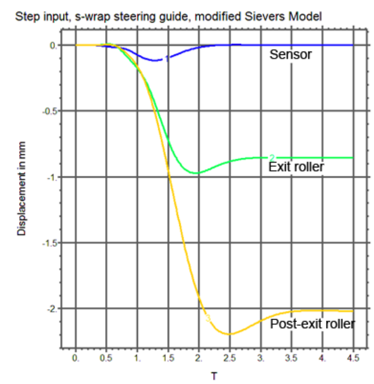
In the graphs of Figure 8 the web appears to make an abrupt change in slope at the guide roller. Small changes in slope can occur across rollers because of shear, as can be seen at the exit roller in (d). However, the change in the guide roller is caused by the fact that the graph is a flattened representation of a 3D geometry. The 90 degree wrap on the guide roller changes the direction of the web, which had been oblique to the machine centerline in the entry span, 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 angular misalignment of the entry span into out-of-plane twist in the exit span. This not only reduces stress in the exit span; it prevents the exit span from undoing the corrective action of the guide.

Importance of the exit span geometry

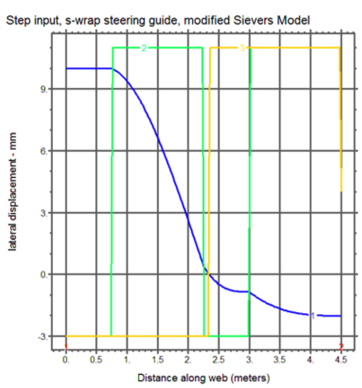
A system like Figure 9, which has its exit span in the same plane as the entry span, performs badly because the pivoting of the guide roller alters the in-plane angle of the upstream end of the exit span. This produces a steering action that causes a large steady state guiding error downstream of the sensor (2.0 mm at the post-exit roller).



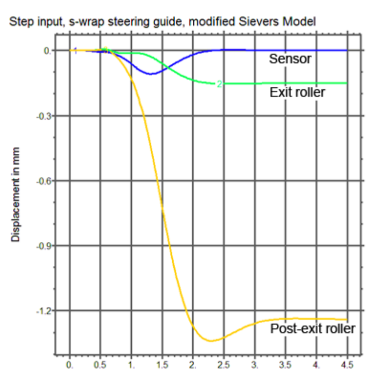
(a) Passline



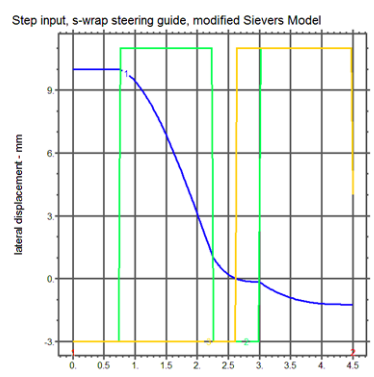
(b) Time response for 1 cm step



(c) Steady state lateral position



(d) Time response sensor half way down exit span



(e) Steady state lateral position sensor half way down exit span

Figure 9
Step response of system
with exit span in the same plane as the entry

The steady state error of the systems like Figure 9 can be reduced by moving the sensor closer to the exit roller.

The last two graphs of Figure 9 show the effect of moving the sensor half way down the span. Error at the post-exit roller has been reduced to 1.2 mm. There will be some sacrifice in system stability, but this may be an acceptable trade off for a significant reduction in error. The seriousness of the loss in stability will depend on the quality of the guiding system. For example, a system using a pneumatic sensor will likely have less stability margin than one using light or ultrasound.

Of course, the best policy is to always use 90 degrees of wrap at the guide roller.

Weave regeneration

Weave regeneration is a phenomenon first reported and analyzed by Lisa Sievers in her 1987 thesis [2]. Her work was sponsored by Kodak Corporation. Apparently, someone there had observed that when a web guide was used to correct a slowly weaving error (in Siever's experiments, a back and forth oscillation of 0.033 to 0.067 cycles per second), it would reappear downstream of the point where it was being controlled. The problem was similar to the one illustrated in Figure 9. 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. 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 subsequent spans.

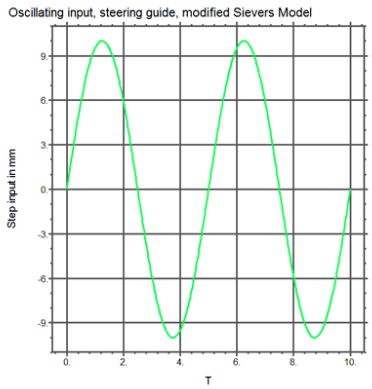
Sievers constructed a lab machine that exhibited this behavior and developed a multi-span mathematical model which accurately reproduced it. I have implemented an improved version of her model [3] in FlexPDE (an FEA software tool for modeling differential equations) and used it to do all the simulations for this paper.

Another way of looking at it

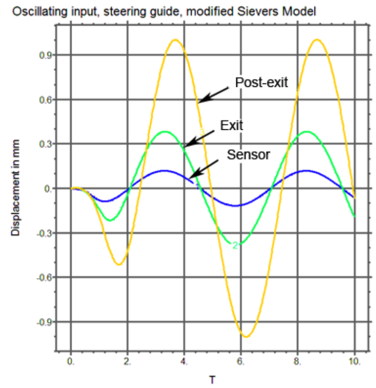
The step response in Figure 8 provides insight into how weave regeneration occurs. Note that although the error due to a step change is always kept very close to zero at the sensor and eventually dies out at every point beyond it (Figure 8 (c)), there are considerable periods of time when it is not zero in the exit and post-exit spans. It is clear that this is caused by the transient shape change. The guide always controls the lateral position at the sensor, but it can't control the lateral slope of the web during times when the web is in the process of changing its shape. At those times, the web is not entering the downstream rollers perpendicularly to their axes and will, therefore, track laterally on them. Thus, a constant oscillatory error, even though it is controlled well at the sensor, continuously forces the web to change its shape, causing slope changes that pass over rollers into downstream spans where they create persistent lateral oscillations.

Simulation of a weaving (oscillating) error

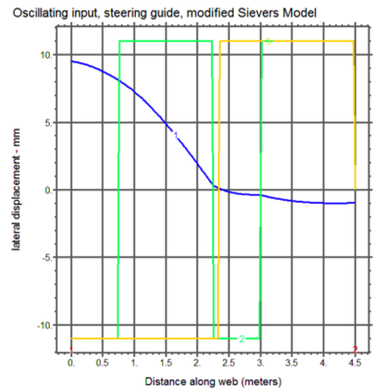
This is illustrated in Figure 10 using the same system parameters as in Figure 8 , but with a 1 cm, 0.2 cycle/sec oscillatory input. The input is shown in (a). Graph (b) shows the time response at the exit and post-exit rollers. The violet curve in each of the graphs (c) through (i) shows the lateral shape of the web at half-second intervals beginning 6.0 seconds after the oscillation started. 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 doesn't help because the guiding system is incapable of controlling the slope at the sensor.



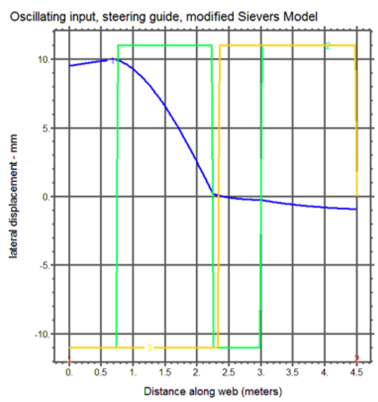
(a) Input



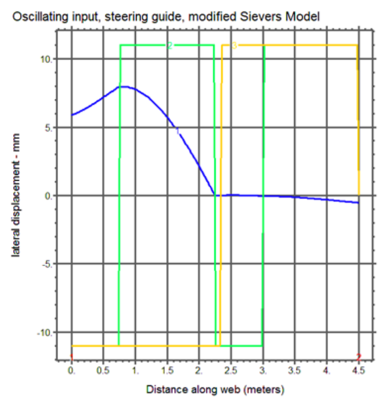
(b) Time response



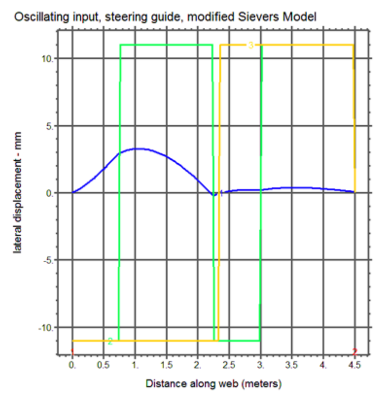
(c) Lateral position at 6.0 sec



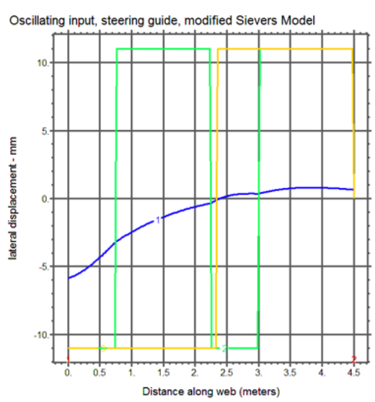
(d) Lateral position at 6.5 sec



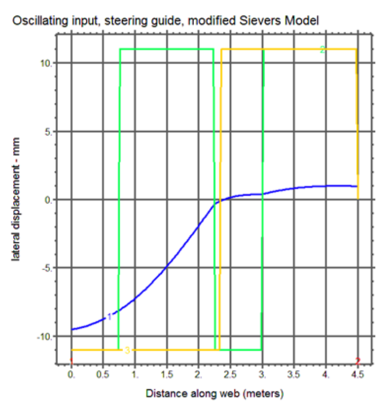
(e) Lateral position at 7.0 sec



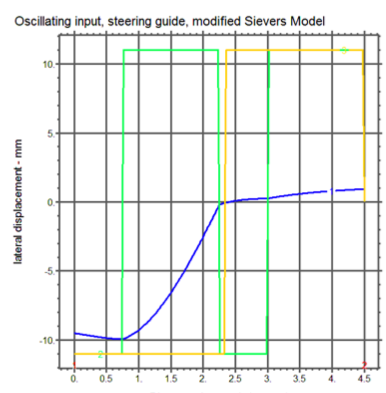
(f) Lateral position at 7.5 sec



(g) Lateral position at 8.0 sec



(h) Lateral position at 8.5 sec



(i) Lateral position at 9.0 sec

Figure 10
Response to an oscillatory input

Shear deformation

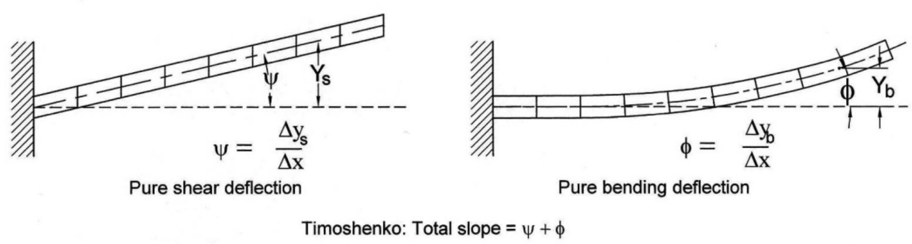
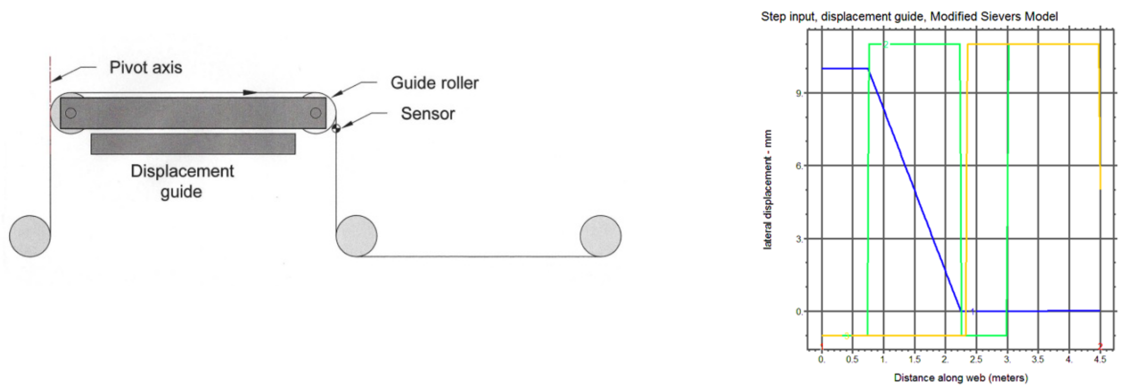


Figure 11
The Timoshenko beam deflects in two ways

Sievers developed two different models[1]. 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 shown in Figure 8 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 in all the simulations in this paper.

The displacement guide: champion of intermediate guides



(a) Passline

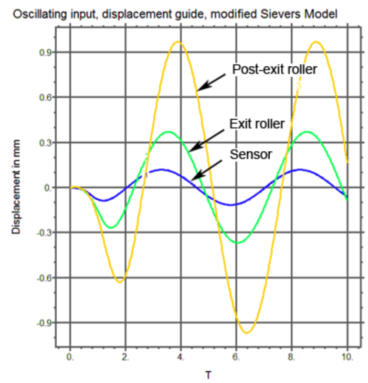
(b) Steady state response to a step input

Figure 12
Displacement guide

The system shown in Figure 12 is the same as the steering system in Figure 7 except that the rollers at the ends of the entry span have been mounted in a frame so that they pivot in tandem about the indicated axis. It has a number of advantages.

[1] There is another model in current use, developed by Young, Kardimilas and Shelton [Young, G. E., Shelton, J. J., and Kardamilas, C. E., "Modeling and Control of Multiple Web Spans Using State Estimation", ASME J. of Dynamic Systems, Measurement and Control, 111, 1989, pp 505-510]. It is functionally equivalent to Sievers' Euler-Bernoulli model, but uses a technique which is particularly convenient for control system design.

1. 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 Figure 13 (b). The web is rotated as though it is a rigid body.
2. 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.
3. Dynamics are simplified because steering is always neutral (no over or under steering).
4. 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.



Time response to
oscillating input

Figure 13
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.

1. 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.
2. Perfect web traction on rollers is assumed at all times and no attention has yet been given to traction requirements during transient conditions.
3. 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.

Things we're sure of

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

1. 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.
2. Reduction in system stability as the sensor is moved down the exit span (never put it in the post-exit span).
3. Steady state offset error when the entry and exit spans are not at 90 degrees.
4. Shelton's steady state beam model for single spans (including shear) is supported well by experiments described in his thesis.
5. 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) [4] [5] and have the potential to make considerable improvements in the capabilities of available systems.

---

[1] Shelton, J. J., "Lateral Dynamics of a Moving Web", PhD Thesis, Oklahoma State University, July 1968
[2] Sievers, L., "Modeling and Control of Lateral Web Dynamics", PhD Thesis, Rensselaer Polytechnic Institute, Troy, NY, 1987
[3] Brown, J. L., "A Belated Appreciation of Lisa Sievers' Thesis", Proceedings of the Thirteenth International Web Handling Conference, June 2015
[4] Seshradi, A., Pagilla, P. R., "Optimal Web Guiding", Journal of Dynamic Systems, Measurement, and Control, January 2010, Vol. 132
[5] Seshradi, A., Pagilla, P. R., "Adaptive Control of Web Guides", 18th IFAC World Congress, August 2011