Controlling Web Position with an End-Pivoted Roller

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Introduction

My interest in controlling lateral position was reawakened by a 1967 Fife memorandum that I found while packing for a move back to Oklahoma last year. In it, John Shelton explains a clever method for applying an end-pivoted guide. It involved attaching the sensor to the pivoting roller bracket and locating it in the entering span. This is something I had completely forgotten about. As I read it again, 46 years later, it occurred to me that explaining the problems of end-pivoted rollers would be a good way to explain some of the mysteries of lateral behavior.

Today, of course, there are better ways to make end-pivoted guides work. For example, a high-performance electromechanical guide can use an electronic sensor to provide the position feedback needed to stabilize the guide. It is not my purpose, however, to discuss the state of the art of web guiding. The applications described here are presented only for the purpose of illustrating the fundamental principles of lateral behavior.

The worst guide of all

Deliberately misaligning a roller is the easiest way to change the lateral position of a web. So, it should be no surprise that end-pivoted rollers have been around since the earliest days of web processing.

It's very common to see an end-pivoted roller at an oven exit. One end will pivot in a spherical roller bearing and the other end will have a screw adjustment that allows the roller to be skewed relative to the path of the incoming web. As conditions in the oven or web change, operators periodically tweak the roller alignment. This works reasonably well because a web will always try to align itself perpendicular to the roller axis. When the roller angle is changed, the web tracks laterally on the roller until it is once again perpendicular. Observation of this behavior leads one very naturally to the idea of motorizing the adjustment screw and using an edge sensor near the roller to control it. But, this never works as expected. Such an arrangement will typically oscillate uncontrollably and this behavior will change with line speed.

A little historical background on lateral dynamics

Webs can't bend like the strings. Laterally, they bend like beams. A mechanical model based on beam theory was first proposed by John Shelton in his 1968 dissertion, "Lateral Dynamics of a Moving Web" [1]. In it, he developed equations that define the shape of a web as it moves between misaligned rollers (it's generally curved like a loaded beam). Knowing how webs bend is interesting, but the real payoff is in a chapter toward the end, titled "Second Order Dynamics of a Massless Web". This is where John combined the curvature information with the effects of the normal entry rule to develop differential equations that define the lateral motion of a web over time as a function of input conditions such as upstream web position, roller angle and position.

John's work was a remarkable achievement because at that time there was virtually nothing in the literature on this subject. It broke new ground and contributed greatly to the establishment of web handling as a respected field of engineering.

As impressive as the dissertation is, though, its potential for better lateral control systems was not initially realized. Control theory was up to the job, but the web equations involve lengthy expressions, full of hyperbolic sines and cosines. These required powerful computers which at that time were far too costly to consider for online guiding systems. That situation has, of course, been steadily improving and, since the 90's, papers describing controllers based on Shelton's work have been appearing with growing frequency.

Another point which should be mentioned is a phenomenon that occurs with any groundbreaking work. As other researchers make new contributions they tend to reorganize and clarify the earlier work, making it more accessible. This can be seen in papers by Young and Reid [2] and by Seshadri and Pagilla [3]. The first parts of these papers provide excellent introductions to lateral behavior.

Avoiding equations

Good illustrations are essential to the explanation of mechanical things. As I began to work on the paper, it occurred to me that I could use an FEA program which is designed to solve 2-dimensional partial differential equations to solve John's 1-dimensional beam equations and use the results to animate a plot of the problem domain so that it would faithfully follow the 2-D shape of the beam as it changed with time. It was no problem to include two spans as well as a differential equation for a guide controller. The model even includes range limits on the guide sensor and actuator. A few examples will be used in the PowerPoint presentation accompanying this paper and can also be seen on my web site at www.NormalEntry.com.

The software also produces time history plots of key variables such as roller position and angles as well as lateral displacement of the web.

Here is a snapshot of the endpoint of a typical animation.

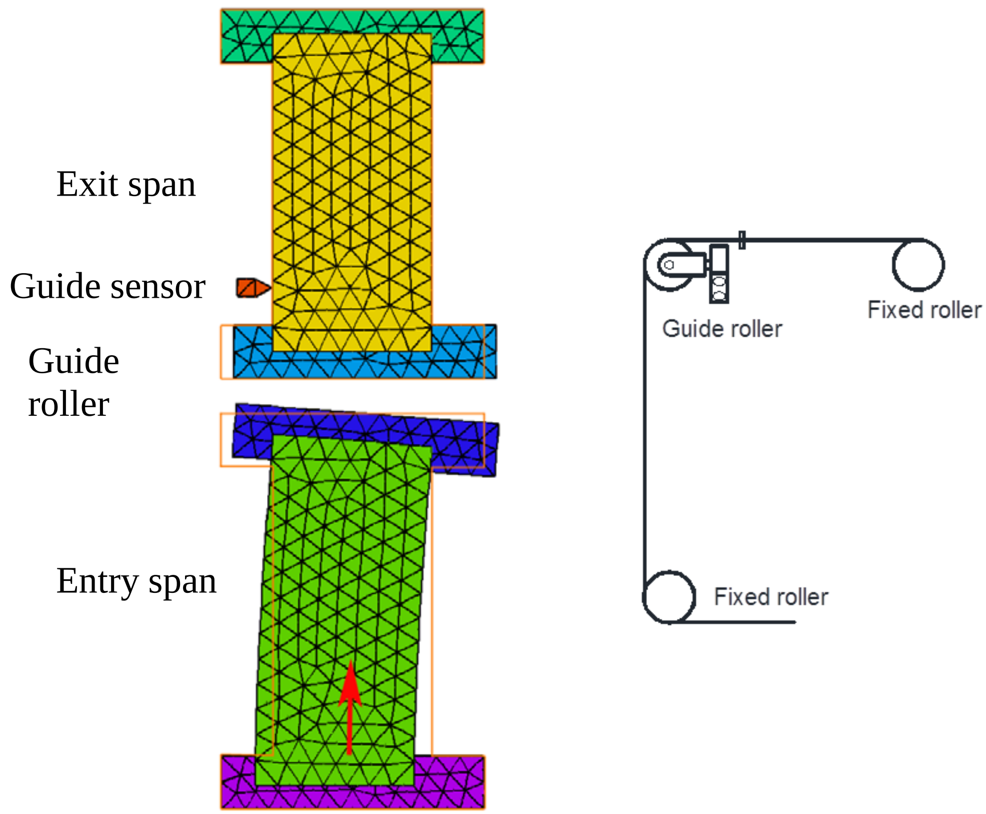

Figure 1
Snapshot of animation showing entry and exit spans of a steering guide
The passline is shown on the right

The guide roller is shown twice, once for the entry span and once for the exit span. In each case the line of sight is perpendicular to the plane of the span. Since the guide roller pivots in the plane of the entry span, none of its angular motion is visible in the exit span view. The location of the guide sensor is shown by the red marker in the exit span. The direction of web motion is always from the bottom up.

There is an orange outline of the original position of the web and rollers to make it easier to follow the changes in position.

In almost all cases, model inputs are chosen which drive the animations far beyond the real world limits imposed by roller traction , slack edge, yield stress etc. This has been done to make the qualitative behavior easy to see. Time won't permit a detailed discussion of these limits. That would require another paper.

For those who feel the need to know them, the model parameters are listed below. For the entry span, they correspond to the test parameters listed in case 1 on page 45 of Shelton's dissertation.

Length (entry span) = 19.5 inches	Tension = 36.7 Lb force
Length (exit span) = 18 inches	Thickness = 0.009 inch
Width = 9.03 inches	Modulus = 450,000 psi
	Line speed = 500 ft/min

Normal Entry

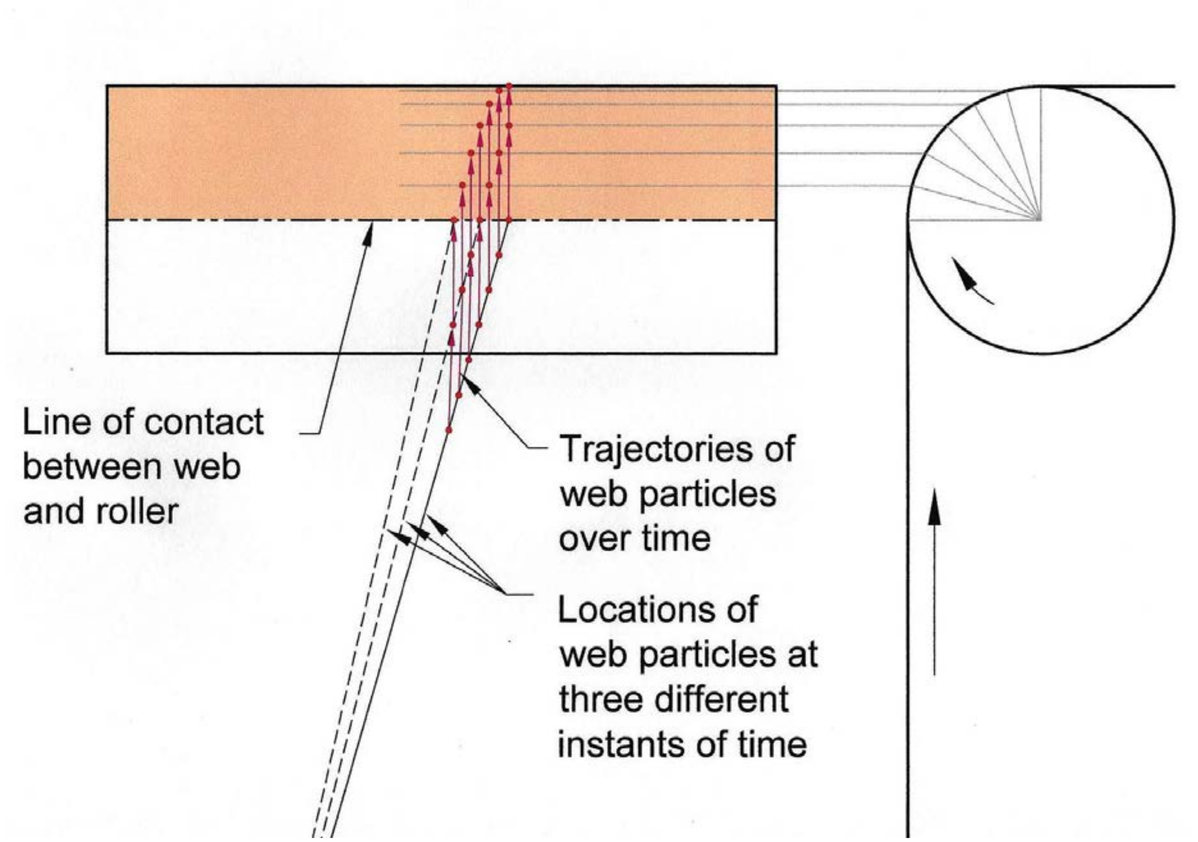

Figure 2
Normal entry

The most important concept in the lateral behavior of webs is the normal entry rule which says that, given adequate traction, the path of a web will always move laterally at the entry to a roller so as to align its motion perpendicular to the roller axis. Figure 2 illustrates why this happens.

The basic principle can be seen by imagining the web as a perfectly flexible string approaching a roller at an angle to the axis and with its location at the upstream end fixed. The fact that the web has stiffness and must bend changes the details of the motion but the basic principle is still the same. As particles of the string approach the line of entry onto the roller, their direction of motion becomes parallel to the motion of the roller surface, so that each successive particle arrives at the point of entry a little to the side (left in this case) of the one before it. Eventually, the string path becomes perpendicular to the roller axis, at which point, each particle entering the roller will follow the same path as the one preceding it. The lateral speed at which the web path moves toward the normal position is approximately proportional to the entry angle.

It’s interesting to note that the web particles themselves do not move laterally. It is the point of contact with the line of entry that moves. However it looks and acts like ordinary lateral motion and for the purposes of this discussion, nothing is lost by calling it that.

Normal is a simpler word for perpendicular, so this behavior is usually called the “Normal Entry Rule” (the web becomes normal to the roller axis). Some practioners prefer to call this the parallel entry rule, referring the web direction to the surface velocity of the roller instead of its axis. However, normal entry has historical precedence and wider use.

There is no normal entry behavior at the exit of a roller.

Web curvature

As mentioned earlier, the web bends like a beam. When it is running in a steady state between rollers that aren’t parallel (for example in a steering guide such as in Figure 1) there is no curvature at the downstream roller. All the bending occurs near the upstream roller, as shown in Figure 3. At times when the web is changing its lateral position (for example, because of a telescoped unwind roll), the shape becomes more complicated and can be curved at both the upstream and downstream rollers. This adds acceleration to the lateral motion.

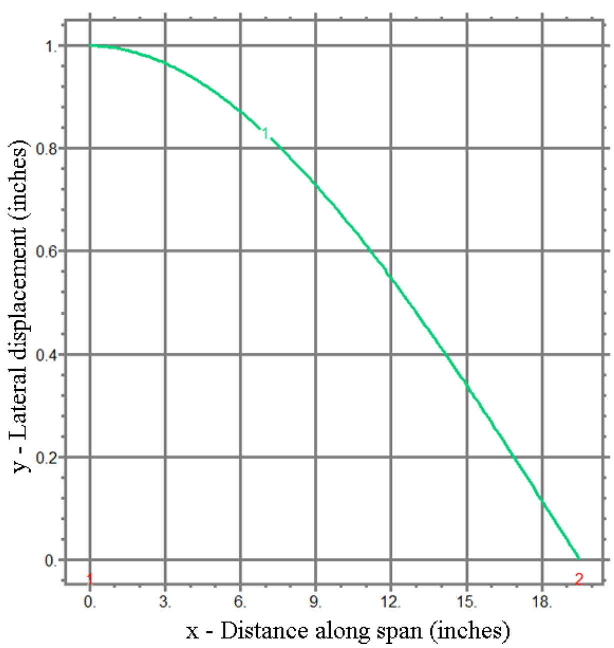

Figure 3
Lateral bending of entry span of Figure 1

Time lag caused by fixed parallel rollers

When the lateral motion at a roller is controlled by the normal entry rule, a lateral disturbance experiences a time lag as it moves past a roller[1]. The delay is proportional to L/V, where L is the span length and V is the web speed. This ratio is known as the first order span time constant τ .

Figure 4 illustrates a sudden shift in lateral position in a span between fixed, parallel rollers. The picture on the left shows a snapshot 0.65 seconds after a ramp change begins at point (1).

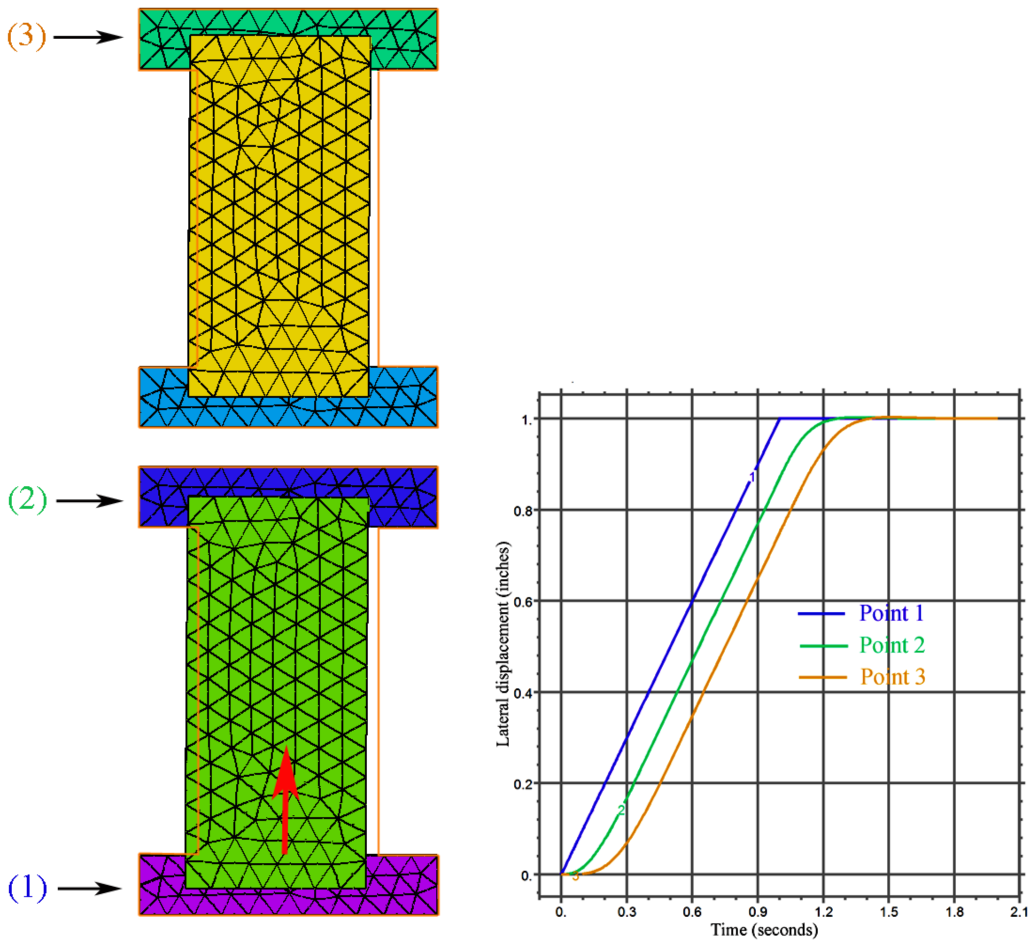

Figure 4
Response to a ramp input between fixed rollers

[1] A control engineer would call the delay "phase shift" to distinguish it from the kind of delay caused purely by the time it takes for the web to move from one point to another.

The displacement at (1) is assumed to be due to a disturbance upstream. As the web moves laterally at the first roller it becomes misaligned with the second roller and the normal entry effect causes it to move laterally to the left at (2). The same thing happens at (3). The graph on the right shows how the displacement at each point changes with time. The line speed is assumed to be 500 FPM. And the ramp increases to 1 inch per second.

Since the first order time constant is equal to the time it takes the web to move through the span, it is easy to assume that its effect on dynamics is simply due to the transport delay from entry to exit, but there is more to it than that. Both L and V enter into the dynamics because of the normal entry rule. The disturbance at roller 1 immediately changes the entry angle at roller 2 (which is inversely related to L), but the lateral position at (2) lags behind (1) because of the time it takes to travel laterally (which is proportional to V). Web curvature makes things a little more complicated by changing the entry angle, but it is still the normal entry rule that controls lateral velocity.

If a disturbance is cyclical (sinusoidal, for example) with a period of oscillation that is on the same order as the first order time constant, it will be significantly attenuated because the downstream displacement can't fully react to the upstream change before the direction of the input motion reverses. This is illustrated in Figure 5 for a sine wave with a period of 0.25 seconds. The attenuation will increase as the period of the disturbance decreases.

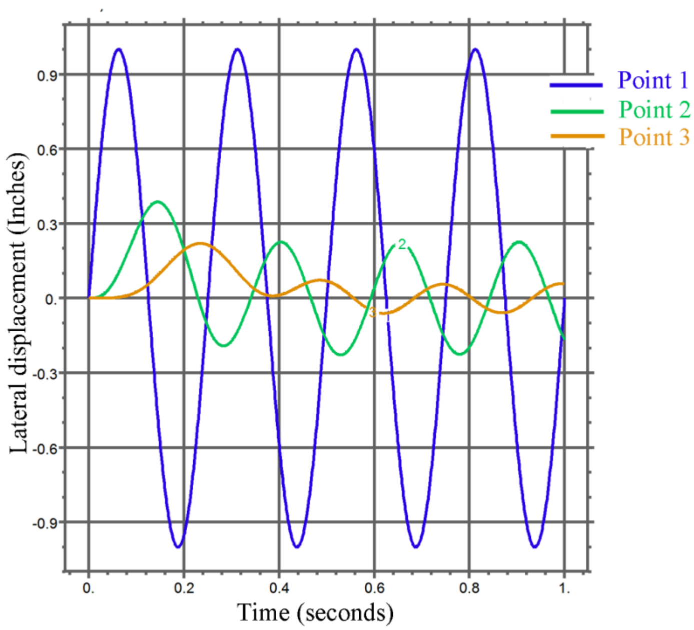

Figure 5
Attenuation and delay of a cyclical lateral disturbance passing over a roller

It can be seen in Figure 5 that there is also a time shift in the waveforms. For sinusoidal waveforms, the time shift is often measured in radians or degrees. It is called phase shift when measured this way. A time shift equal to one complete cycle of the waveform is 360 degrees or 2π radians. The waveform at the exit of the entry span (point 2) has been shifted approximately 135 degrees relative to the entry (point 1). A control engineer would say that the roller is causing 135 degrees of phase lag. The waveform at the exit of the next span (point 3) has been shifted relative to its entry (point 2) by approximately the same amount.

The behavior shown in Figure 5 means that rollers are low pass filters that attenuate and phase shift periodic disturbances as they progress through a process line.

Controllers

Suppliers of guiding systems have to be conservative because customers expect their control systems to be adjusted once and then forgotten, yet they face many challenges. Among these are:

- The dynamic behavior of the web itself usually degrades system stability. For example, putting a single roller between a guide roller and its sensor will add enough time lag to completely destabilize a system. Schemes to compensate for the lag are complicated by the fact that it changes with line speed, tension and web properties.
- Structural vibration (which might otherwise be acceptable) can be misinterpreted by a guiding system as web position error. Inertial reaction to the guide's response can reinforce the vibration causing it to build up to unacceptable levels.
- Systems are limited by the amount of distortion the web can tolerate.
- Efforts to increase speed of response or accuracy usually aggravate all of the above.

In the early years of web guiding, suppliers used a type of automatic control system that provided a reasonably safe compromise between simplicity, speed and accuracy called a rank 1 controller. You've probably got many of these in your plant today.

In guiding systems, a rank 1 controller takes the form of one in which the actuator output is not position. It is velocity. The controller forces the velocity to be proportional to an input from the guide sensor (position in, velocity out). When talking about the controller characteristics it is customary to assume that the control loop is open – meaning that there is no feedback of the output to the input. Closing the control loop converts the velocity of the actuator into position.

A typical system might have a gain of 30 inches per second per inch of error (30 mm/s/mm). This means it would take 0.067 inches of error at the sensor to produce 2 inches per second at the actuator. The actuator could be either a hydraulic cylinder or a motor-driven ball screw. The sensor may be either pneumatic or electronic. The simplest such system relies on a pressure signal from an air-jet sensor to move the spool of a hydraulic valve which, in turn, controls the flow of fluid to a hydraulic cylinder.

In systems today, rank 0 controllers have become popular. A rank 0 controller forces the actuator position (rather than its velocity) to be proportional to the error at the guide sensor (position in position out). A rank 1 controller can be converted to a rank 0 controller by using a signal from a position sensor on the actuator to create an internal control loop that converts velocity to position. The drawback of a rank 0 controller is that it will not bring a static error to zero. There will always be a small residual error at the sensor. The advantage of a rank 0 controller is that it knows and controls the exact position of the guide roller at all times. This facilitates coordination of guiding system operation with operation of the process line. For customers who wish to have zero static error, some vendors offer an integrating function similar to that found in PID controllers.

As mentioned earlier, computer technology is now equal to the task of implementing adaptive control techniques which are capable of improving performance and stability across a wide range of operating conditions. Systems of this kind will likely be necessary to meet the high performance demands of roll-to-roll organic semiconductor manufacturing. This is currently a focus at the OSU Web Handling Research Center.

Shifting and pivoting

Guiding systems have little tolerance for time lag. To insure stability, system suppliers rely on two strategies. First, they keep the lag as small as possible by locating the sensor close to the guide roller and never putting a fixed idler roller between the guide roller and the sensor. Second, they design the guide mechanisms so that the roller shifts laterally as it pivots. The lateral shift provides immediate feedback that keeps the system stable. In an ideally designed application, the relationship between the lateral shifting and pivoting puts the web in exactly the right position to cancel the incoming error while at the same time putting the roller at an angle that satisfies the normal entry condition.

An end-pivoted guide is a good example of what happens with only pivoting.

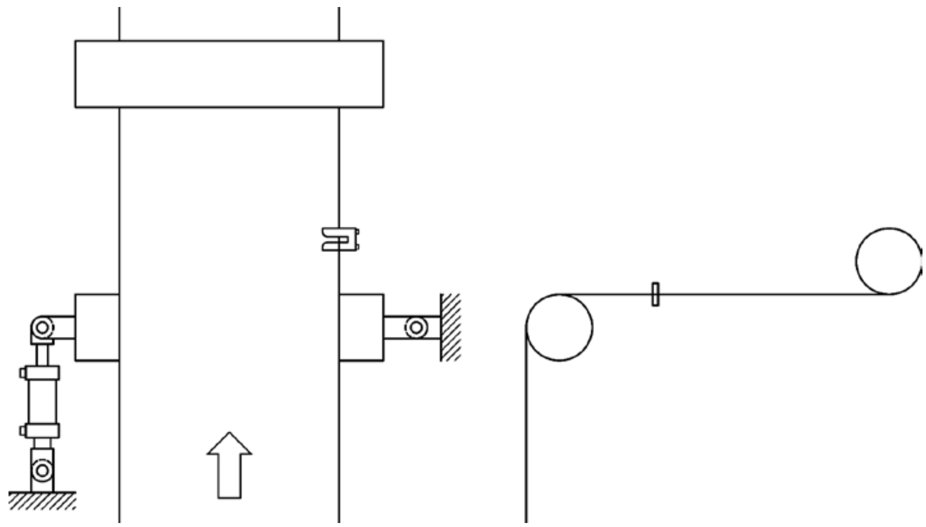

Figure 6
An end-pivoted guide

As explained in the introduction, when a controller closes the loop between the sensor and actuator in Figure 6, it will typically oscillate uncontrollably with a frequency which will vary with line speed.

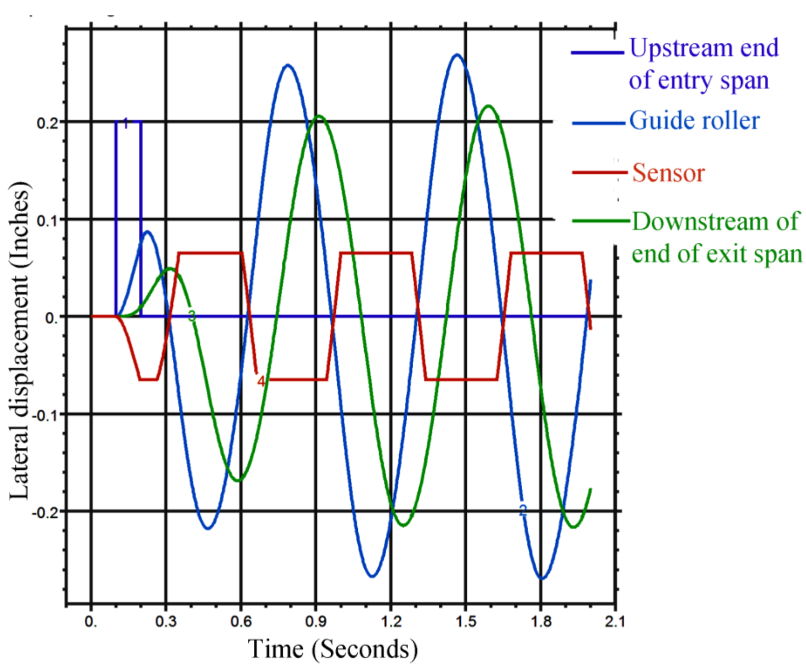

Figure 7
Oscillation of end-pivoted roller with sensor in the exit span

The root of the trouble is that the pivoting roller produces no immediate feedback to the control system. The only lateral motion is due to the normal entry effect and that comes with a phase lag that is too big for a typical controller. Figure 7 shows such a system where a brief pulse has triggered a growing oscillation. It will continue to grow until it reaches the limits of the system actuator.

Shifting without pivoting is also a bad idea. It provides a short-term quick response, but can't hold the web in position long-term.

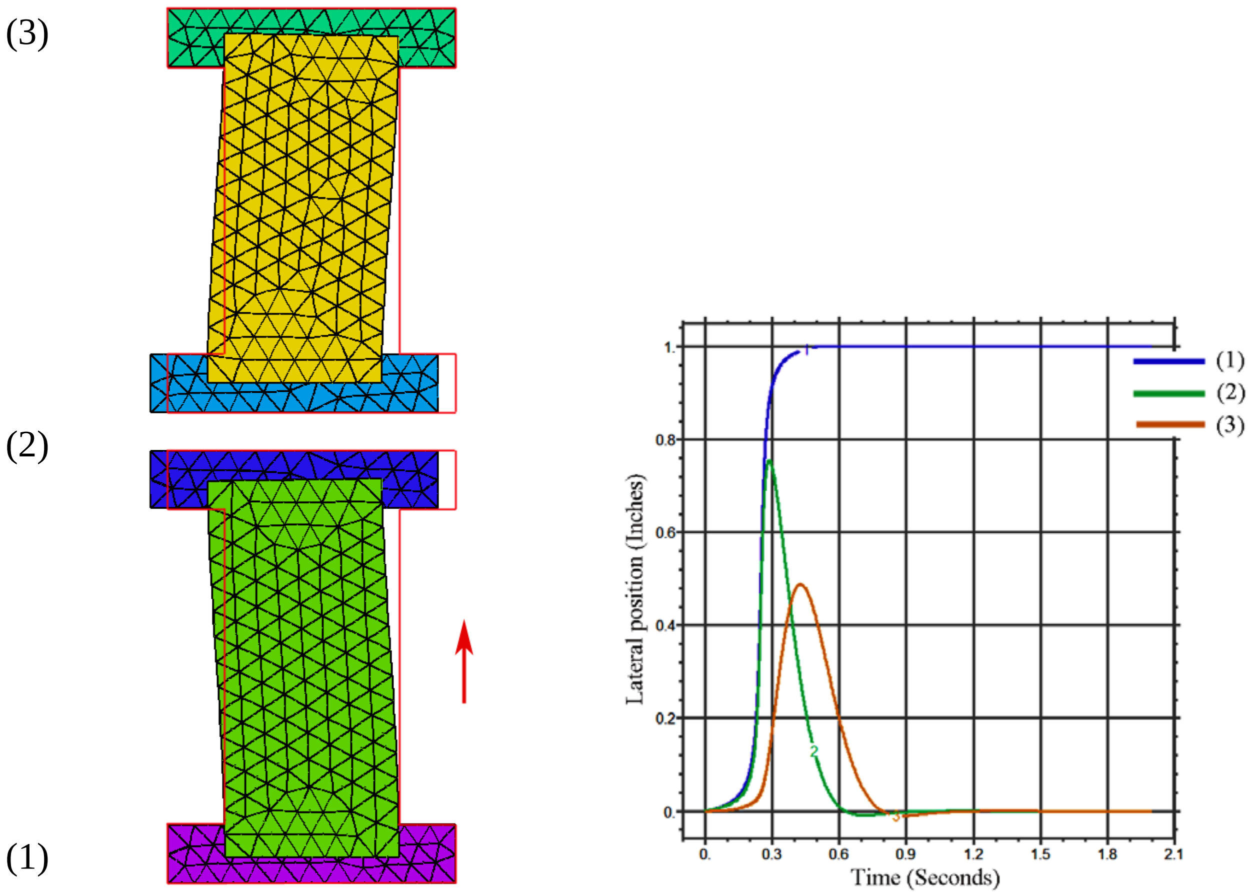

Figure 8
Shifting a roller without pivoting

In Figure 8 the roller at location (2) has been shifted 1 inch to the left. The web is carried with it and becomes misaligned with both rollers (2) and (3). Then, as the graph on the right shows, the normal entry effect brings the web directly back to its initial position, even though the roller remains in its shifted position. If such an arrangement were used in a web guiding system it would continue to shift the roller until the actuator bottomed out.

The steering guide

The best web guides combine shifting and pivoting. Shifting provides an immediate, short-term correction and pivoting enables normal entry to provide a stable long-term response.   A steering guide is the most common example.

On the left side of Figure 9 a steering guide is shown after it has corrected a ramp displacement at roller (1). A rank 1 controller was used in the model, so the graph on the right shows a steady state error at the sensor which falls to zero when the ramp ends.

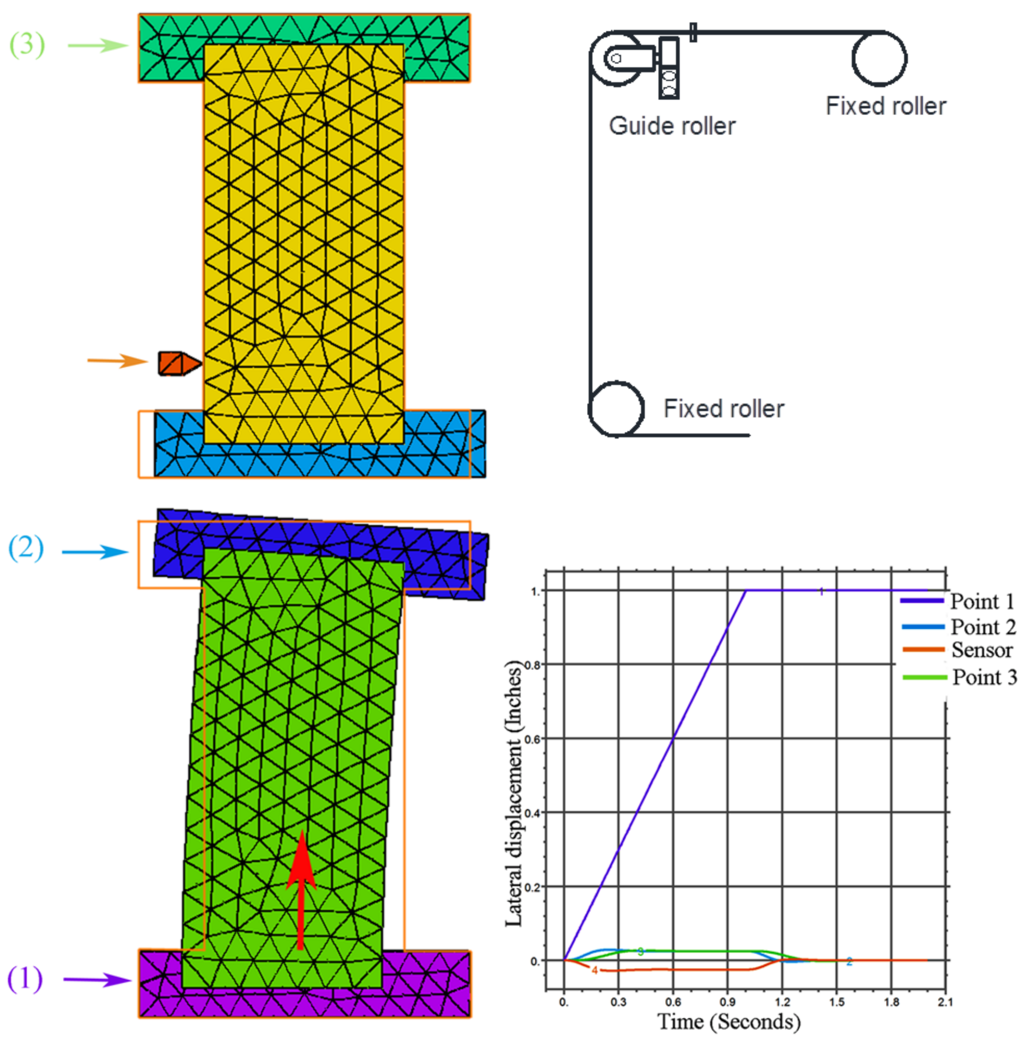

Figure 9
Steering guide

Roller (1) is fixed. The web is assumed to ramp 1 inch to the left on roller (1) over a period of 1 second, due to some unspecified disturbance. A guide sensor is fixed to the stationary machine frame and measures the deviation of web position immediately following the guide roller (2). The error is amplified and used to control the velocity of an actuator which shifts roller (2). Roller (2) is mounted on inclined linear bearings so that it pivots as it shifts. The pivot point, called the instant center, is located upstream. If the web were perfectly flexible like a string, the ideal location for the instant center would be at the upstream roller (1). With that condition, the lateral shifting and pivoting would be perfectly coordinated so that a short-term shift would put the roller at the perfect angle to satisfy the long-term normal entry condition. This is called the neutral steering condition. If the instant center is farther upstream of the ideal location, the guide will be in an understeering condition which means that the web will have to continue to track laterally on the roller after its initial response in order to achieve normal entry. If the distance to the instant center falls short of the ideal location, the guide will be in an oversteering condition which means that the guide roller will pivot beyond the normal entry condition in its initial response. The web will then have to track slowly back to achieve a steady position.

Curvature due to bending causes a reduction in the effective radius of motion of the web. The ratio of the radius of web bending to the length of the span ranges from 1 to 2/3, with most applications falling close to the 2/3 value. Therefore, the ideal pivoting radius (neutral steering) for most steering guides is 2/3 of the entering span length.

The idea of the 1967 memo

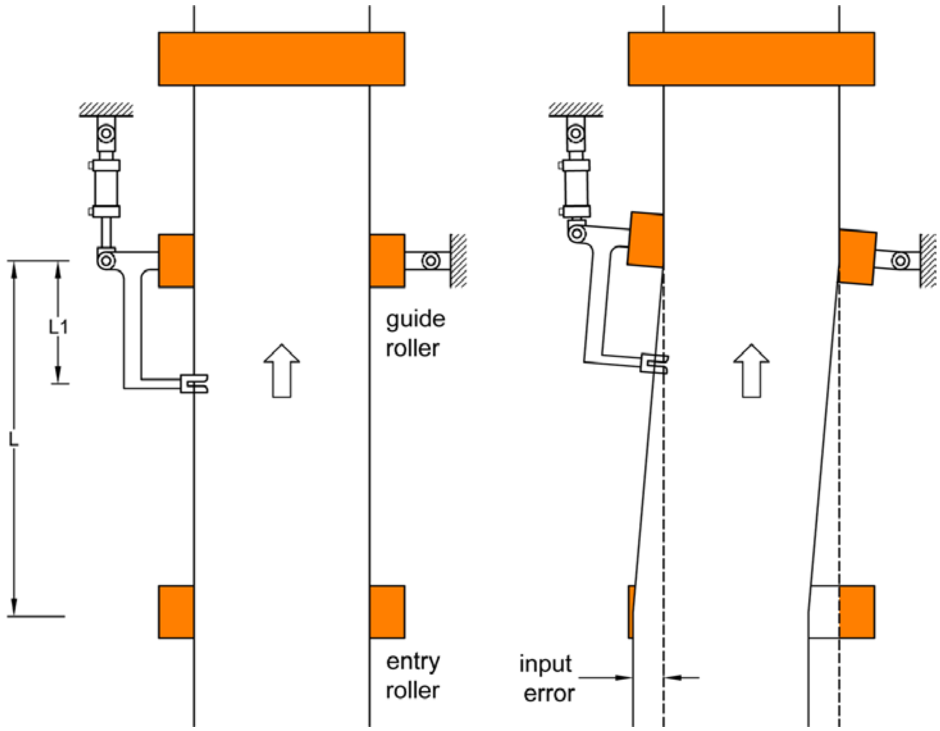

Figure 10
End-pivoted roller with entering span feedback

Figure 10 illustrates the basic idea of the 1967 memo. It assumes that the web behaves like a string. The sensor is mounted on a bracket that pivots in the entering span with the guide roller. When an error appears at the entry roller, the sensor sees part of it, causing the control system to tilt the roller until the error at the sensor is zero. The geometry of the motion is such that the tilted axis of the roller will be exactly normal to the new path of the web (if web curvature is ignored). Thus, at the guide roller, the web is unaffected by the upstream disturbance andwill keep the same position it had before the error occurred. This is completely different than the usual web guide. The web isn't being "steered" into agreement with the position of a fixed sensor. Instead, the roller is being steered by the sensor so that the web doesn't move away from its original position. Accuracy can never be as good as a conventional guiding system because there is no error feedback from the virtual guide point at the guide roller. But, there are many applications for which it is good enough.

The memo mentioned that a small steady state error could be expected "due to curvature of the web" and that this could be minimized by keeping the sensor close to the guide roller. That's true, but if L1 gets smaller than L/4 the system will be only marginally stable. Stability is best when the sensor is farthest from the guide roller (assuming the lengthy support structure for the sensor is rigid), but that is where the effect of web curvature will have the worst affect on accuracy. A good compromise location is L1 = L/3. Figure 11 shows the results of a simulation using this value.

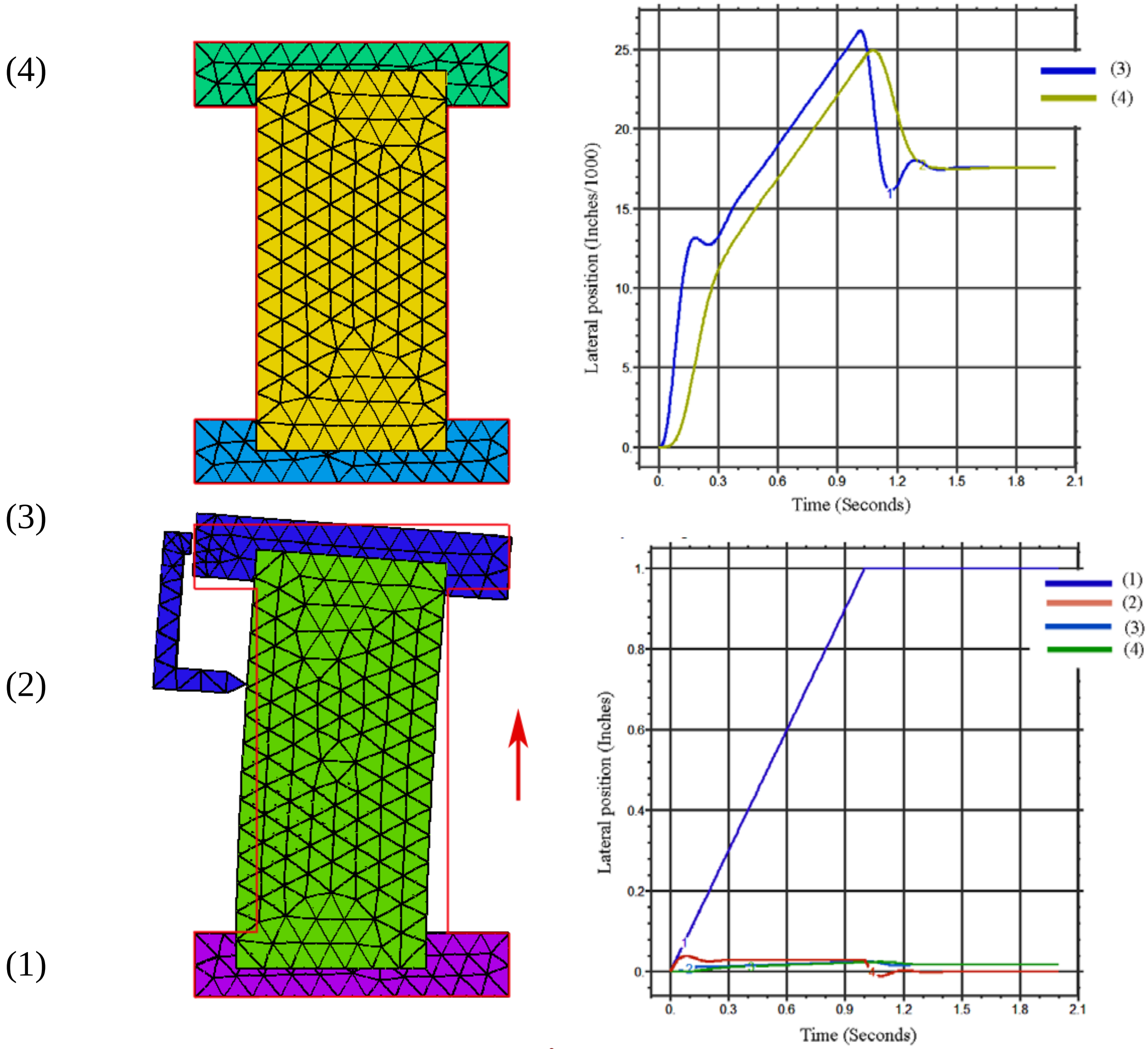

Figure 11
End-pivoted guide with L1 = L/3

The upper graph shows that the steady state curvature error at the guide roller would be 17.5 thousandths of an inch for a 1 inch error at the entry roller - point (1).

These days, the system might be improved somewhat by using electronic feedback, but it would still be a poor substitute for a steering or displacement guide.

There is a related idea that works better (You can see it at OSU)

The high speed winder at the Web Handling Research Center is designed to run the web in both directions. This presented a particular challenge for the intermediate guiding systems. It's my understanding that John Shelton and Bruce Feiertag proposed the arrangement shown in Figure 12. In the forward direction, it is a conventional displacement guide, which, of course works quite well. In the reverse direction, it is like the end-pivoted guide of the previous section. It steers the guide rather than the web and it's stable because it satisfies the need for immediate feedback.

It has a stability advantage over the end-pivoted design because of better web dynamics.

Like the end-pivoted design, this guide lacks error feedback from the virtual guide point, but it does not have any error due to curvature and accuracy is adequate for the machine's purpose.

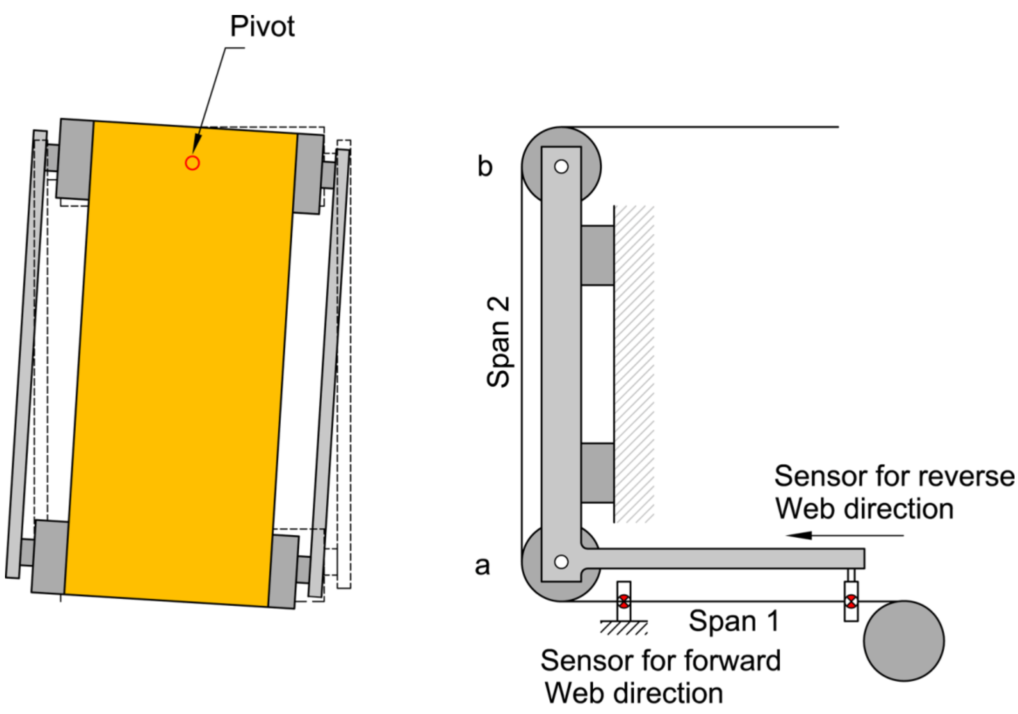

Figure 12
Bi-directional displacement guide

When running in the reverse direction, the guide operates to keep the web from moving laterally at roller (b).

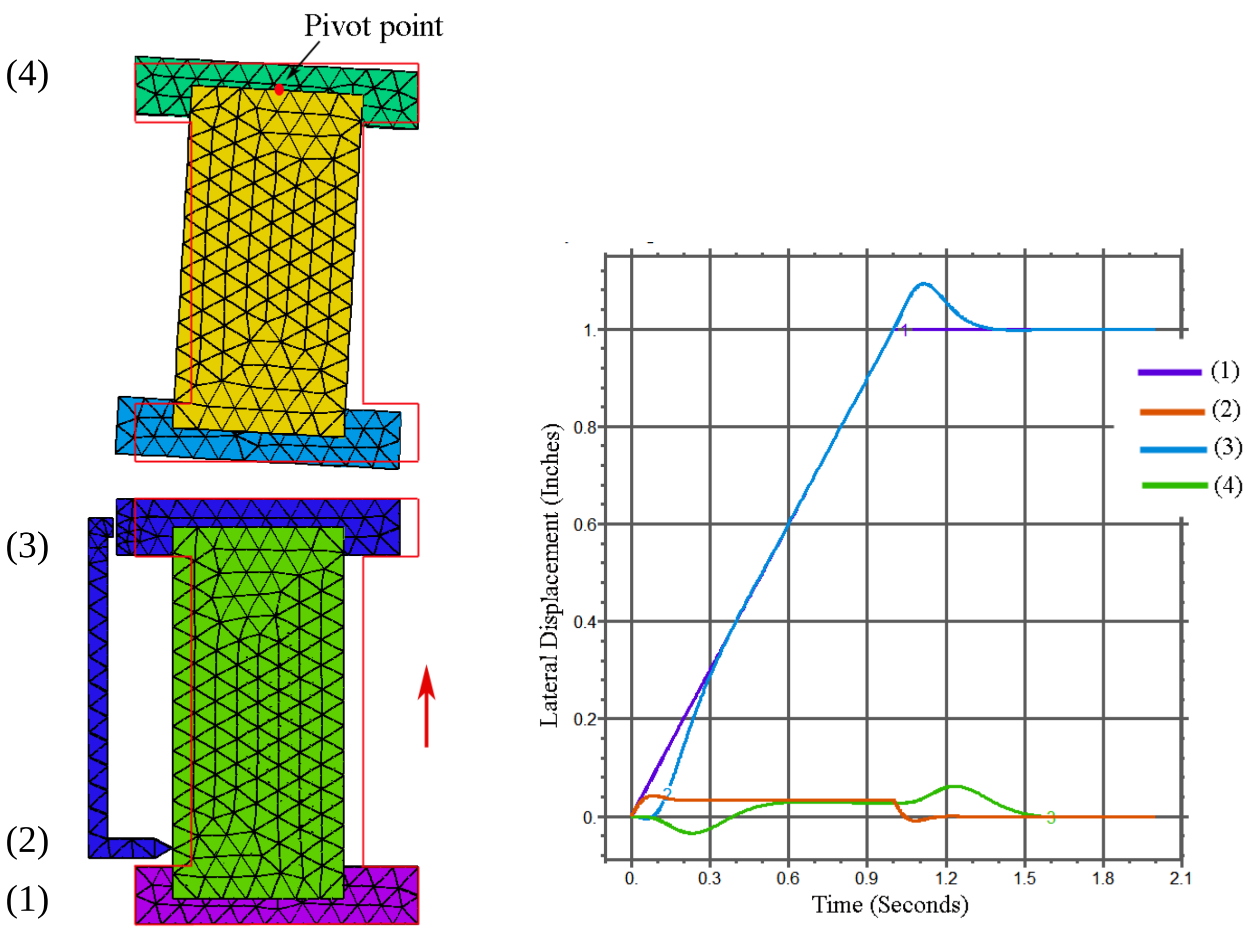

Figure 13
Response of the bi-directional displacement guide
(running in reverse)

In Figure 13, roller (1) is fixed. Roller (3) pivots with roller (4) about the pivot point. Roller (4) is where the web is being held in position. Curves 1, 3 and 4 show the position of the web on the corresponding rollers. Curve 1 is the incoming ramp error. Curve 4 is the error that remains at the exit of the guide. Curve (2) is the error input to the control system.

The guide is quite stable. A rank 1 controller is used in the model so there is a following error of approximately 0.040 inch at roller (4) while the ramp is changing and zero error at the end of it.

It is apparent from the diagram on the left that there is very little bending of the web in either span (which means there will be minimal web dynamics). In the steady state there is theoretically no bending.

[1] Shelton, J. S., “Lateral Dynamics of a Moving Web, Dissertation, Oklahoma State University, 1968

[2] Young, G. E., & Reid, K. N., “Lateral and Longitudinal Dynamic Behavior and Control of Moving Webs”, ASME Journal of Dynamic Systems, Measurement, and Control, June 1993, Vol. 115/309

[3] Seshadri, A, & Pagilla, P., “Optimal Web Guiding”, ASME Journal of Dynamic Systems, Measurement and, Control, January 2010, Vol 132/011006-1