IMPACTS OF A 90 DEGREE TWIST ON LATERAL WEB DYNAMICS

By

Jeremy Carrle, Steve Lange, and Shan Ba
Procter and Gamble
USA

ABSTRACT

Twists are sometimes used to turn or provide passive lateral control for narrow webs in those cases where space for a sufficient twist span length (to avoid a wrinkle) is achievable. This paper uses the finite element method to study the lateral dynamics of a web downstream of a 90 degree twist in response to an upstream lateral disturbance. A designed experiment of 46 different finite element runs was used to study the interactions among different material, geometry, and input variables. Specifically, the frequency response for downstream cross-direction position was modeled as a function of the disturbance frequency, disturbance amplitude, span length, wrap angle and material stiffness. Nominal strain was held constant. A composite Gaussian process model was fit to the resulting data to facilitate a deeper and more holistic interpretation. Excellent attenuation of the disturbance amplitude and interesting interactions with the applied frequency and twist span length were shown.

NOMENCLATURE

1^{st} roller	termed the "entry" roller
2^{nd} roller	termed the "twist" roller
3^{rd} roller	termed the "next" roller
Δc	applied lateral shift of web, mm
E	Young's Modulus of the base web, kPa
h	base web thickness, mm
L	span length, mm
W	total unstrained web width, mm
R	Roller radius, mm
V	web velocity, m/s
ε_{md}	nominal machine direction strain
μ_s	static coefficient of friction between rollers and web
θ_w	wrap angle on roller after twist, degrees

A	mean centerline offset, mm
ω	frequency of centerline offset, Hz
θ_t	twist direction, degrees

INTRODUCTION

Cross machine position variation in web handling is a common and well known problem caused by a number of sources of which we will provide just a few examples. The rollers of a web processing machine can be mis-aligned, causing mis-tracking. The manufacturing processes for webs can create cross-machine variation that leads to inherent curvature (camber) that steers the web in the lateral direction. And similarly, webs can also be intentionally non-uniform as when two web parts are continuously or discontinuously combined.

One historically effective and well known way to manage or control lateral variation is by twisting the web 90 degrees. This method is effective and low cost given that there is enough span length available to twist the web without causing wrinkles. Wide webs require greater span length to safely twist and for this reason, the twisting technique may be prohibitive. Amos [1], Todd [2], and Bauer [3] used a twist in a web handling device for the purpose of improved lateral tracking. These references disclosed the devices and some explanation for how they worked but did not characterize the details of how well they worked.

This paper focuses on how effectively lateral disturbances are removed after a single 90 degree web twist. The web was forced to move in a sinusoidal pattern, entirely to one side of the centerline, while the cross-direction (CD) web position at the roller just after the twist and at the next roller (without a twist) was analyzed. An experimental design comprising 46 finite element computer simulation runs was used for this investigation.

SIMULATION SETUP AND METHOLOGY

Web and Process Variables

The simulated web path included three 50 mm diameter idler rollers with a twist between the entry roller and the twist roller. The span length between the twist and next rollers and the wrap on the entry and next rollers were fixed at 500 mm and 90 degrees, respectively. The twist span length (L), wrap on the twist roller (θ_w), and direction of twist (θ_t) were varied. The frequency (ω) and amount of centerline shift (Δc) were also varied (Figures 1 and 2). Table 1 lists the parameters and variable ranges used in the virtual experiment.

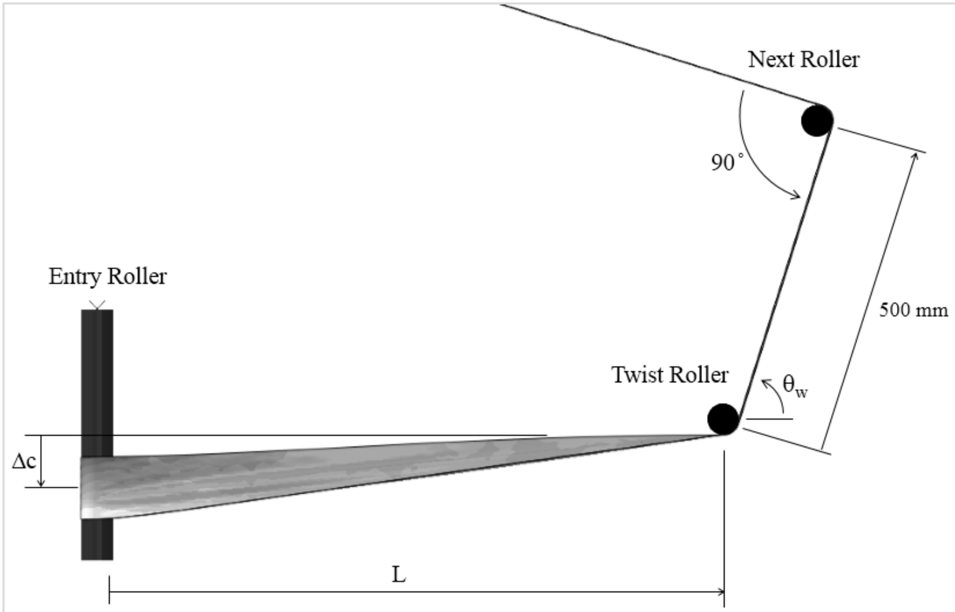

Figure 1 – Fixed parameters and geometric variables for lateral shift, span length, and wrap angle.

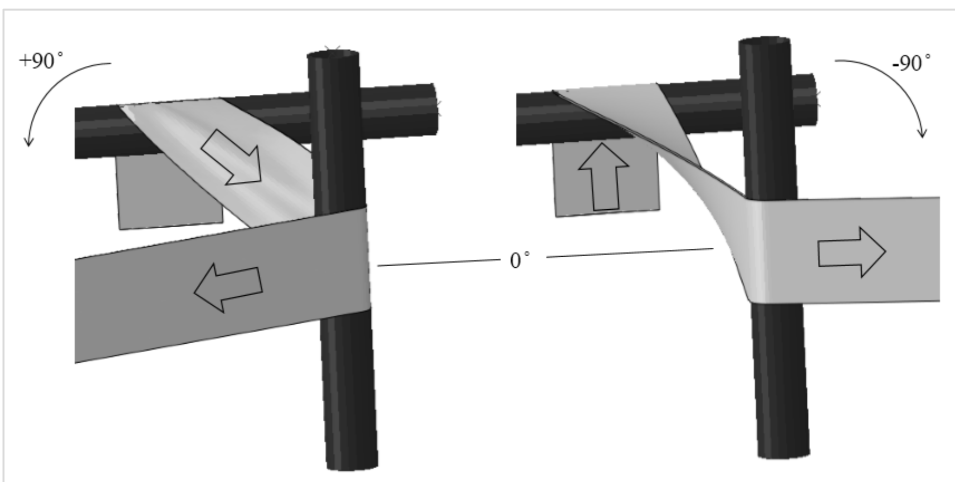

Figure 2 – Diagram showing a twist of positive or negative 90 degrees.

Parameters	Value
ε_{md}	0.015
W (mm)	100
h (mm)	0.1
R (mm)	50
V (m/s)	~1
μ_s	0.3
Variables	**Range**
E (MPa)	5 - 500
L (m)	1 - 2
θ_w (deg)	20 - 90
ω (waves/span)	0.5 - 5
A (mm)	0 - 100
θ_t (deg)	-90 OR +90

Table 1 – Web Parameters and Variable Ranges

EXPERIMENTAL DESIGN

We ran the simulation based on a two-stage sequential experimental design in order to develop a surrogate model to study the effects of each input factor on the responses. The first-stage design is a maximum projection Latin hypercube design [4] to identify important input factors, and then we augmented it with a second-stage space-filling design which was optimized to extract information from the system in the most efficient way. After obtaining the simulation data, we fitted composite Gaussian process models [5] to accurately approximate the computationally expensive simulation model and study its input factor effects.

Simulation Computational Parameters

Dassault Systèmes' ABAQUS/Explicit version 6.13 software was used as the finite element analysis tool. Simulation time for each run was 14 seconds to allow steady state mis-track conditions to be achieved at the downstream roller. Shell elements with a mesh size of 3.33 mm were used. To apply the prescribed shift (and frequency of shift) the web was delivered in such a way that its motion was completely prescribed up until the tangent point with the first roller.

Measurements of Cross-Direction Position

The cross-directional edge positions were measured on the twist roller, just after the twist on the entry roller, and at the next roller after the twist. These edge positions on the rollers were averaged and reported with respect to a perfectly aligned and centered twist. It follows that a reported position of zero means that that the web was perfectly aligned and centered after the twist. Figure 3 shows how the input web motion was applied and where the web position was measured on subsequent rollers.

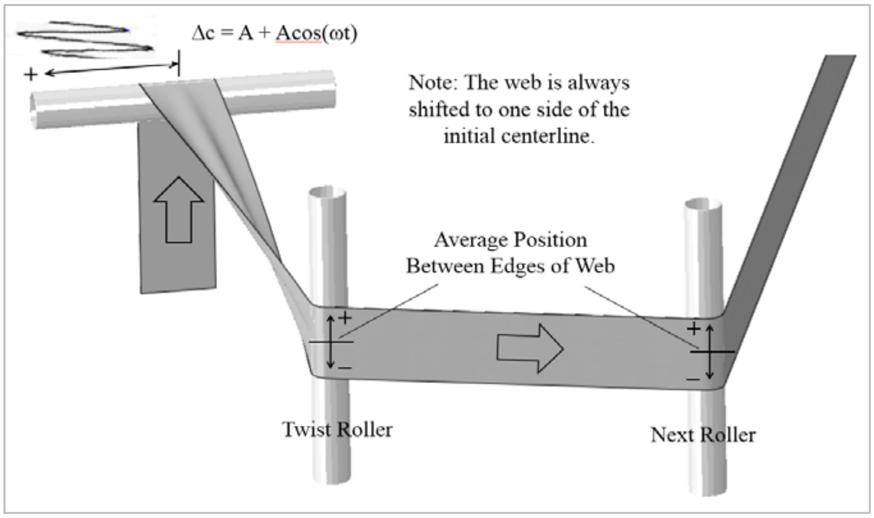

Figure 3 – Illustration showing where motion was applied to the incoming web and where the lateral motion was measured on the exit rollers.

The steady state output (considered as 9 - 14 seconds) was analyzed to determine the mean CD shift as well as the range of the response. A diagram representing these values is shown in Figure 4. In the steady state time period data was collected every 0.02 seconds and a standard statistical mean and range were calculated for these points.

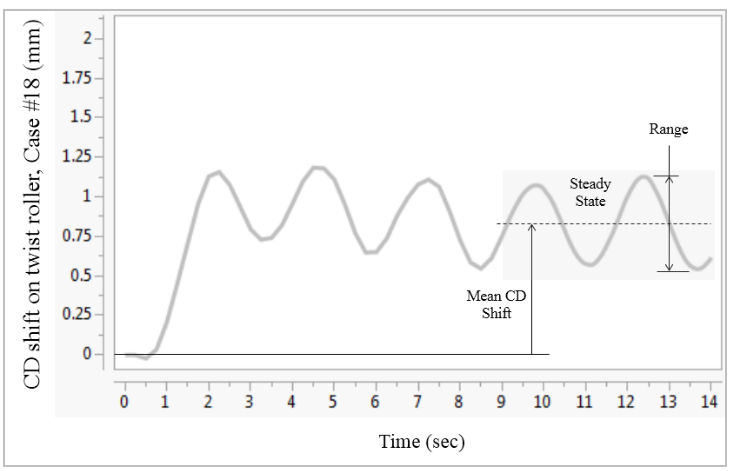

Figure 4 – Diagram explaining how CD shift output at the exit rollers was characterized.

Many conditions revealed a frequency component to the cross-direction position output. The steady state output was also analyzed for spectral frequency peaks using SAS/JMP Pro v11 software.

RESULTS AND DISCUSSION

<u>How effective is a twist at reducing cross-direction motion?</u>

The results indicate that a twist is very effective at reducing the amount of cross-direction motion. We applied relatively large shifts in position, up to 2X the width of the web, and after the twist the lateral motion was typically only a small fraction (roughly 4-6%) of the motion applied before the twist (Figure 5). The outlier shown in Figure 5 was a point that was added after completion of the designed experiment for the sole purpose of creating and investigating maximum shift conditions. For this outlier, the twist length and strain were much smaller verses recommendations [6] and significantly smaller than in all other cases. Even this outlier shows an average mis-track that is only 23% of the average CD shift applied at the entry roller.

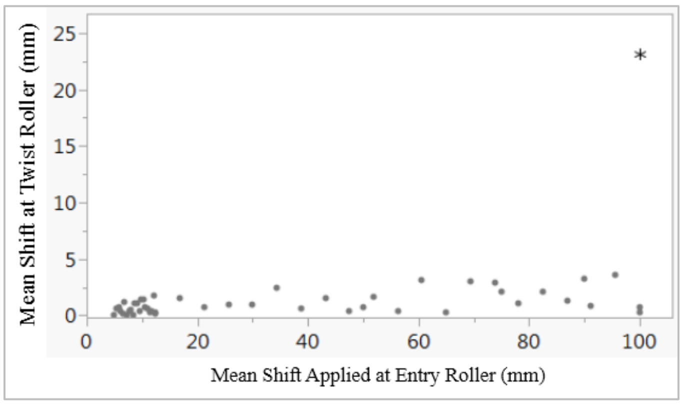

Figure 5 – Scatter plot for the magnitude of the shift at the twist roller vs. the mean disturbance amount applied to the web. All cases shown as well as a special case, #47, indicated with an asterisk.

<u>What direction does the web move on the twisted roller?</u>

The answer is not straight forward given that we saw cases where the direction of downstream lateral web motion did not correlate with the direction of the twist (as defined in Figures 2 and 3). For example, a positive twist did not always lead to a positive downstream shift and a negative twist did not always lead to a negative downstream shift (Figure 6).

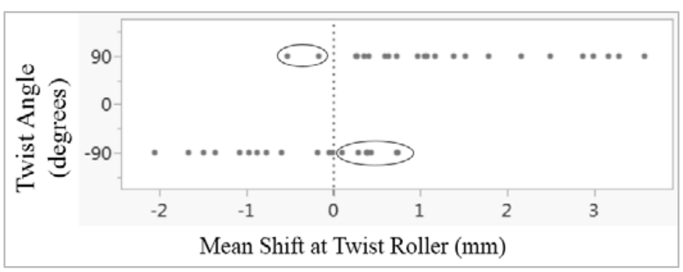

Figure 6 – Scatter plot showing mean shift verses twist angle. All cases shown. Cases in which the sign of the twist angle did not agree with the sign of the mean CD shift are circled.

The general trend was that the twist direction agreed with shift direction. A positive 90 degree twist led to upward motion of the web on the rollers (as shown in Figure 7). Conversely, the web typically shifted in the negative direction (downward) if the web was twisted by negative 90 degrees.

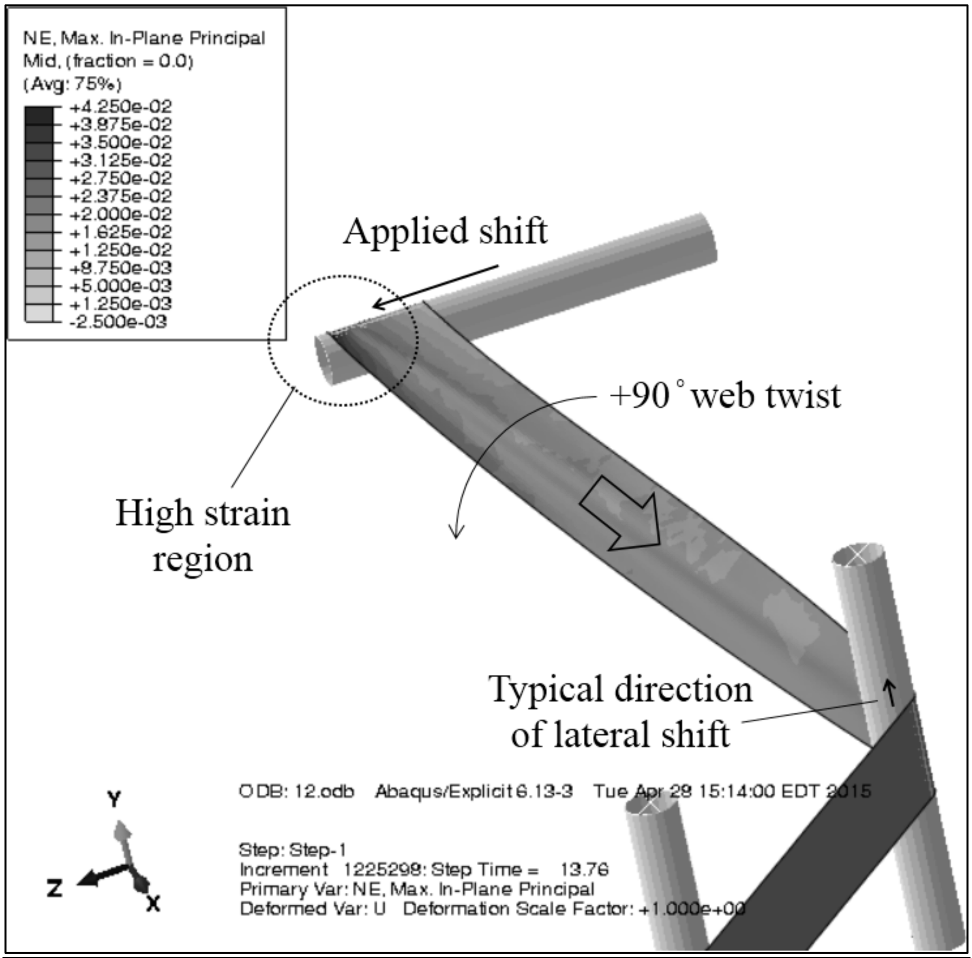

Figure 7 – Simulation image showing the region of locally higher strain and the typical direction of lateral movement on the twist roller.

The authors believe that there are multiple phenomena in action but that the typical result is driven by an overall lessening of the path length for the outside of the web, which is at higher strain (Figure 7). When the web raises on the twist roller (for a positive 90 degree twist) the path length for the outside edge slightly decreases while the path length for the inside edge increases by the same amount, however, because the outside edge is at higher strain, it is favored and the net result is that the web raises. An opposing mechanism, due to the normal entry rule, causes complex bending of the web and a shift in the opposite direction. Possibly, this mechanism accounts for the smaller number of cases where the lateral web motion did not correlate with the direction of the twist.

How does the exit frequency compare to the input frequency?

When an oscillatory behavior was evident on the exit rollers it was typically at a frequency identical to that applied at the entry roller. Figure 8 shows a typical case where the frequency of the CD position on the exit rollers matches the applied frequency at the entry roller. Note, however, that the signals were not synchronized and a time lag was evident.

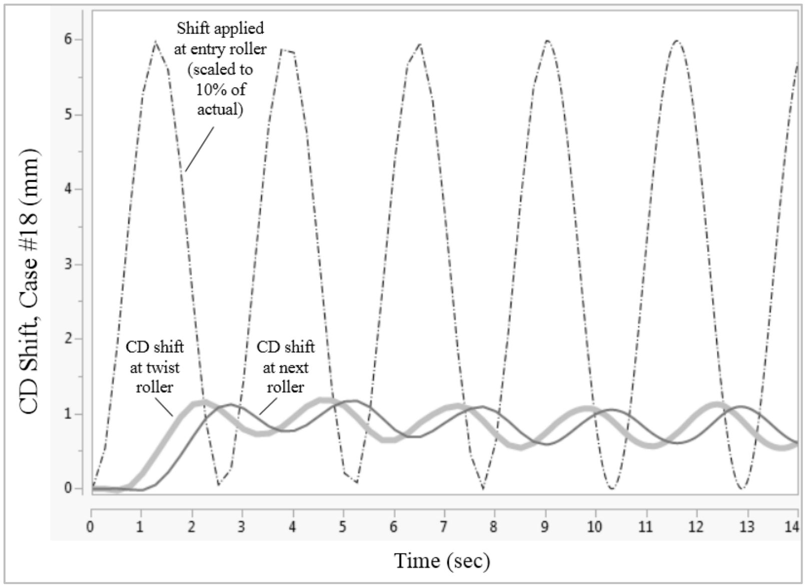

Figure 8 – CD web shift verses time for the applied shift at the entry roller and for the twist and next rollers, case #18. Note: The motion at the entry roller was scaled such that the detail of each trace could be seen on the same scale.

There were also less typical cases (Figure 9) where there appeared to be additional and lower frequencies superimposed. A significant portion of cases were also relatively ‘flat’ and there appeared to be very little variation about the mean steady state shift. 17 out of 46 cases where either flat or had low levels of random looking noise and no obvious frequency content.

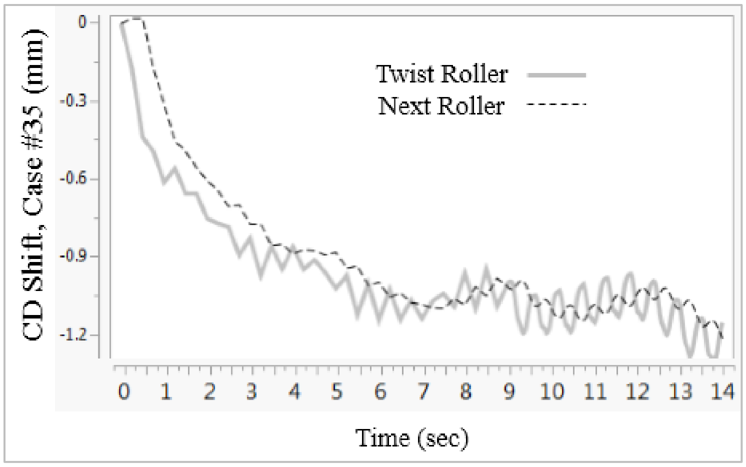

Figure 9 – CD web shift for the twist and next rollers, case #35.

<u>What affects the mean shift and the range of the shift seen at the exit rollers?</u>

Input amplitude, input frequency, and span length each had significant effects on the CD shift behavior. A fitted composite Gaussian process model helped better understand the relationships and interactions between these variables. The relationships are shown in Figure 10 for the mean shift at steady state. Span length as well as the magnitude of shift applied at the entry roller had significant effects. Increasing span length, especially above 1.5 m (or 15 X the web width) significantly reduced the mean shift at the exit rollers. An increase in the amount of applied CD shift correlated with an increase in the amount of CD shift at the exit rollers although the impact of this increase seemed to flatten at relatively high values greater than one web width (100 mm).

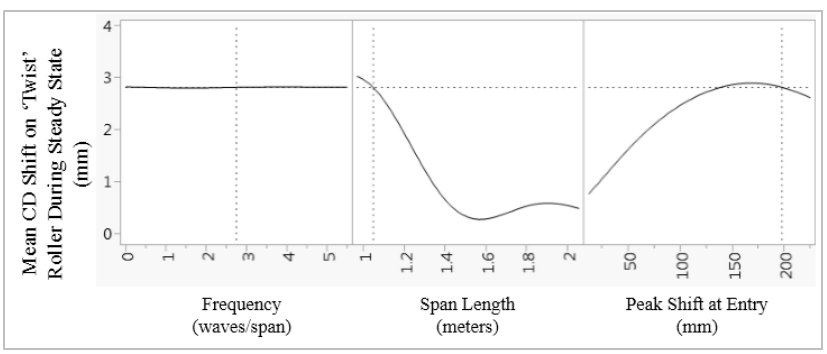

Figure 10 – These plots are screen shots from a profiler of the composite Gaussian process model created in SAS/JMP Pro v11. In its live form it will interactively change as the user slides and sets the x-axis variables.

The composite Gaussian process model also helped understand the range of the CD shift at steady state. The interactions were slightly more complex for the range response and so two sets of plots are used in Figure 11, the top row of plots are for higher frequencies and the bottom row of plots are for lower frequencies. The frequency of the shift applied at the entry roller had the biggest impact. At frequencies above 2 waves/span the range measured at the exit rollers was greatly reduced and the other variables of span length and applied shift amplitude made very little difference. Interestingly, at lower input frequencies, span length and shift amplitude did interact - an increase in span length decreased while the applied amplitude increased the range.

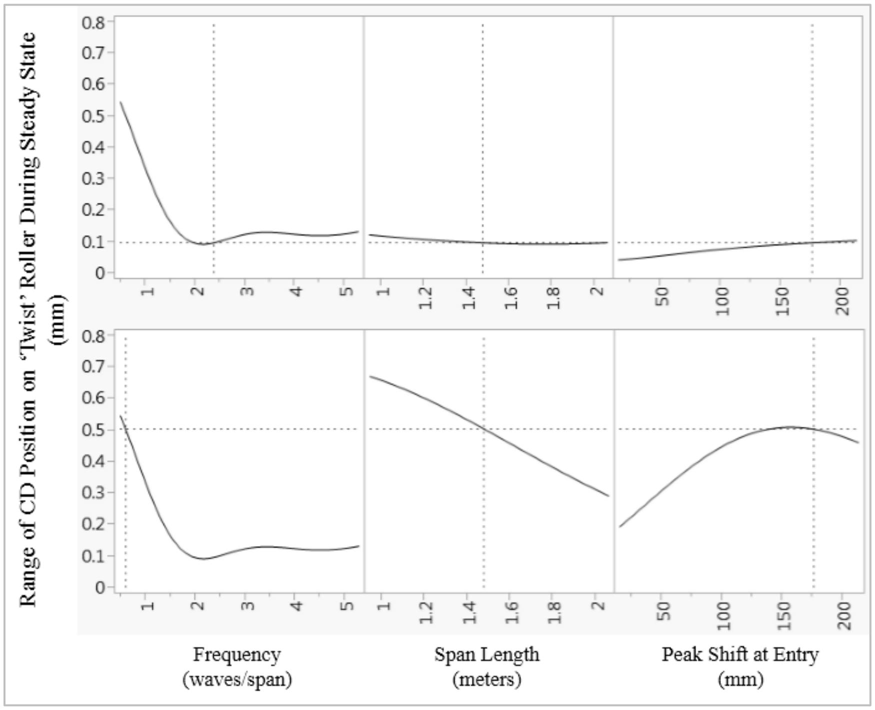

Figure 11 – These plots are screen shots from a profiler of the composite Gaussian process model created in SAS/JMP Pro v11. In its live form it will interactively change as the user slides and sets the x-axis variables.

CONCLUSIONS

A 90 degree twist, within the variable ranges studied, is very effective at removing lateral web motion on downstream rollers. There are complex mechanisms at work that caused the web to shift in either direction on the downstream rollers relative to the twist direction, however, there seemed to be a dominant force within the ranges we tested that favored one direction. An increase in span length can further reduce the variation from this dominant source. Presumably, variation from other, more complex mechanisms may not necessarily be decreased by an increase in span length. Oscillatory behavior (about some mean shift) was reduced when the applied disturbance was at higher frequency and the span length was longer.

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