MODELING AND COMPUTER SIMULATION OF ZERO SPEED SPLICE UNWINDS

By

Prabhakar P. Pagilla
Texas A&M University
USA

ABSTRACT

A computer program for conducting model simulations for zero speed splice unwinds is described in this paper. A typical unwind system consisting of the unwinding material roll, festoon, dancer, and pull rolls is considered. The developed computer model is general enough to be applicable to a variety of unwinds containing these components. The paper also provides a procedure for determining zero speed splicing parameters when the characteristics of the festoon and the splicer, such as number of carriage rollers, festoon capacity, clamp and dwell time, etc., are given; this method can be employed for the selection of splicing parameters, such as acceleration and deceleration profiles, splice diameter, spindle speed profiles, etc. The computer model can predict the transport behavior of webs through the unwinds; this was verified by comparing data from model simulations and experiments on a production unwind. The computer program can be used to evaluate different scenarios of unwind operation prior to actual implementation on production unwinds. Thus, providing a significant benefit in terms of operational efficiency as well as improved process capability.

1 INTRODUCTION

Web lines for manufacturing personal care products often use zero speed splice unwinds with festoons to facilitate roll change. These unwinds are a leading source of waste and delay, and for most part are set up using trial and error. Scientific knowledge and systematic procedures that would help in the selection of configuration and operational parameters for the unwind process are limited. This is a significant problem given that there are thousands of zero speed splice unwinds in existence in the industry today. Recent emphasis by companies to use lighter basis weight webs in order to reduce cost and employ higher speeds to expand into global markets has exacerbated this problem even more; lighter webs are more prone to wrinkles, neck-down and web breaks. Therefore, there is a significant need to develop systematic scientific procedures based on mathematical models and computer simulation of those models to efficiently setup the unwind system and run the unwind process. The goal of this paper is to describe the development of a computer simulation program for zero speed splice unwind based on the mathematical models associated with web spans, rollers, and the festoon.

1

Three aspects associated with unwinds are essential in developing systematic guidelines for the unwind operation during zero speed splicing: (1) a suitable model that reflects the web transport behavior as well as the dynamics associated with the mechanical components; (2) analysis of the model to optimize speed profiles and select reference values for transport variables that would lead to improved transport behavior in the unwind; and (3) model simulation to evaluate system behavior for a variety of possible operating conditions and experimental validation. These three aspects will be described in this paper.

The unwind model is developed by considering existing literature on the topic and some key observations on production unwinds; we will also draw from the existing work in references [1] through [11] on dynamics of accumulators and related control systems. A typical unwind roll change strategy is employed for the development of the model and its validation: (1) over speed of the expiring unwind roll to fill festoon; (2) deceleration of the expiring roll to zero-speed; (3) web cut from the expiring roll and splicing of the web from the new roll to the web in the festoon; and (4) acceleration of the new roll to the desired line speed. Although this sequence of events is quite standard from an unwind operation viewpoint, one has to systematically consider the selection of speed profiles and the time associated for each event while considering the physical constraints of the unwind, such as festoon capacity, clamp and dwell time, etc. The model consists of governing equations for web speed on each roller and tension in each span, which can be conveniently used to set up a computer model simulation. The paper will describe such a computer model developed in Matlab/Simulink. In addition to the computer model, the paper will also describe a systematic procedure for determining splicing parameters, such as acceleration and deceleration rates, start diameter, etc.

NOMENCLATURE

a_s	:	Acceleration of the new roll (fpm/s).
d_s	:	Deceleration of the expiring roll (fpm/s).
D_{ex}	:	Diameter of the expiring roll when it stops for splicing (in).
D_{fs}	:	Diameter of the expiring roll at the beginning of festoon fill "Start Fill Diameter" (in).
h	:	Web thickness (feet).
J_i	:	Roller i inertia.
N	:	Number of rollers on carriage; number of festoon spans = $2N$.
R_i	:	Roller i radius.
S_f	:	Total festoon stroke; 100% of festoon stroke (feet).
t_{cd}	:	Clamp + Dwell time (s).
v_c	:	Carriage velocity (fpm).
v_f	:	Festoon fill rate (% of festoon fill/s).
v_i	:	Web transport speed on roller i (fpm).
v_p	:	Nominal line speed (fpm).
W	:	Web length released/accumulated from the festoon (feet).
w	:	Web width (feet).
x_c	:	Carriage position (feet).

| y_a	:	Decrease in festoon fill height during acceleration (% of full height).
y_{cd}	:	Decrease in festoon fill height during clamp and dwell (% of full height).
y_d	:	Decrease in festoon fill height during deceleration (% of full height).
y_f	:	Festoon fill height at the beginning of decel (% of full height).
y_m	:	Maximum festoon fill height (% of full height).
y_s	:	Festoon fill height at steady-state operation (% of full height).
β_f	:	Factor to determine unwind overspeed ($=\beta_f v_p$) at the beginning of deceleration.
ω_i	:	Roller i angular velocity
ρ	:	Web material density

2 GOVERNING EQUATIONS
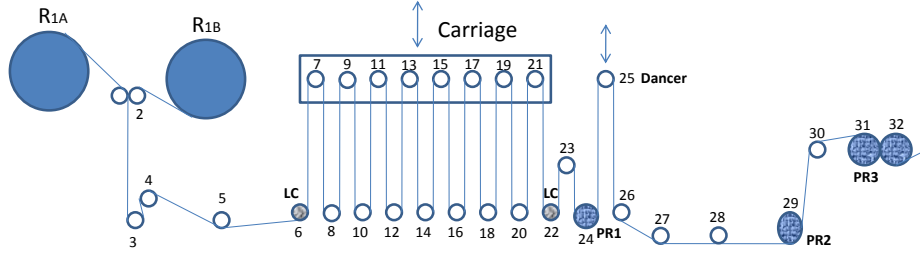
Figure 1 – Unwind Line Sketch. LC: Load Cell Roller; PR: Pull Roll; R1A, R1B: Unwind Rolls

The computer model was developed for the unwind system shown in Fig. 1; the rollers are numbered from 1 through 32 as shown. The unwind system consists of dual unwind rolls (R_{1A} and R_{1B}), an automatic splicer at roller number 2, idle rollers and spans, a festoon, load cells at the exit and entry of the festoon, a dancer, and three pull rolls downstream of the festoon. The unwind system is decomposed into four modules:

Module 1: Unwind roll to the entry span of the festoon; governing equations for the (1) unwind material rolls, (2) idle rollers and spans from the unwind roll to the festoon, and (3) unwind roll control are considered.

Module 2: Festoon carriage, spans and rollers; governing equations for (1) the carriage, (2) web spans with varying span length and idle rollers within the festoon, and (3) carriage control are considered.

Module 3: Exit span of the festoon to Pull Roll 2; governing equations for (1) the dancer, (2) idle rollers and spans, and (3) Pull Roll 1 are considered.

Module 4: Pull Roll 1 to Pull Roll 3; governing equations for (1) idle rollers and spans and (2) Pull Roll 2 are considered.

Two key governing equations were used to develop the dynamic models for each module: web velocity on a roller and web span tension. The web velocity on a roller is based on torque balance on the roller and the web span tension model is

a nonlinear differential equation obtained from applying conservation of mass to a control volume encompassing the span. Two key assumptions that were used to obtain these governing equations are: (1) there is no slip between the web and the roller surface, that is, the peripheral velocity of the roller in the region of web wrap is equal to the web velocity and (2) the web is assumed to be elastic in deriving the nonlinear differential equation for the evolution of tension in a span. These two governing equations were used to create dynamic models for each module. In addition, there are other models for primitive elements such as linear dancer and the material roll that were used. The radius calculator was implemented as per the equation given in [5]. One main exception to the above is that the governing equation for web tension in festoon spans is different from the web spans whose steady-state length remains the same. The span tension equations reported in [2,3] were used for web tension in festoon spans.

2.1 Module 1 Governing Equations

The governing equation for the unwind roll angular velocity is given by

$$\frac{d}{dt}(J_1\omega_1) = \tau_{f1} + \frac{R_1 t_1}{GR_u} + u_1 \tag{1}$$

$$\dot{\omega}_1 = \frac{1}{J_1}\left[\tau_{f1} + \frac{R_1 t_1}{GR_u} - \dot{J}_1\omega_1|u_1\right] \tag{2}$$

where

$$J_1(t) = J_{rotor} + \frac{(J_{core} + J_{matl}(t))}{GR_1^2}; \quad J_{matl} = \frac{\pi}{2}w\rho\left(R_1^4(t) - R_{c1}\right); \quad \dot{R}_1 = -\frac{h\omega_1}{2\pi}.$$

We will consider n_1 rollers (including the unwind roll) between unwind roll and first festoon roller; for the sketch shown in Fig. 1, there are five rollers (1, 2, 3, 4, 5). The idle roller angular velocity dynamics is given by:

$$J_i\dot{\omega}_i = \tau_{fi} + R_i(t_i - t_{i-1}).$$

Assuming no slip condition for web wrap on the roller, web velocity is related to angular velocity as $\omega_i = v_i/R_i$. Thus, the governing equations for the web velocity on roller and span tension are given by:

$$\dot{v}_i = \frac{R_i}{J_i}\tau_{fi} + \frac{R_i^2}{J_i}(t_i - t_{i-1}); \quad i = 2:n_1 \tag{3}$$

$$\dot{t}_i = \frac{EA}{L_i}(v_{i+1} - v_i) + \frac{1}{L_i}(t_0 v_1 - t_1 v_2); \quad i = 1:n_1 \tag{4}$$

2.2 Module 2 Governing Equations

We will assume N rollers on the carriage; thus, there are $N+1$ rollers at the bottom of the festoon for a total of $n_2 := 2N+1$ idle rollers within the festoon. The governing equations for web velocity on the rollers and festoon spans ($2N$ festoon spans) are given by

$$\dot{v}_i = \frac{R_i}{J_i}\tau_{fi} + \frac{R_i^2}{J_i}(t_i - t_{i-1}); \quad i = n_1 + 1 : n_1 + n_2 \tag{5}$$

$$\dot{t}_i = \frac{EA}{x_c(t)}(v_{i+1} - v_i + \dot{x}_c) + \frac{1}{x_c(t)}(t_{i-1}v_i - t_i v_{i+1} - t_i\dot{x}_c); \quad i = n_1 + 1 : n_1 + n_2 \tag{6}$$

4

The motion of the carriage is governed by

$$\dot{x}_c = v_c \qquad \{7\}$$

$$M_c \dot{v}_c = u_c(t) - M_c g - \sum_{i=n_1+1}^{n_1+n_2} t_i \qquad \{8\}$$

2.3 Module 3 Governing Equations

Consider n_3 rollers (Roller numbers 23 through 28 in Figure 1) in this module, including one driven roller (PR1) and remaining idle rollers. The governing equations for web velocity on rollers and span tensions are given by:

$$\dot{v}_i = \frac{R_i}{J_i}\tau_{fi} + \frac{R_i^2}{J_i}(t_i - t_{i-1}) + \frac{R_i}{J_i GR_i}u_i; \quad i = n_1 + n_2 + 1 : n_1 + n_2 + n_3 \qquad \{9\}$$

$$\dot{t}_i = \frac{EA}{L_i}(v_{i+1} - v_i) + \frac{1}{L_i}(t_0 v_1 - t_1 v_2); \quad i = n_1 + n_2 + 1 : n_1 + n_2 + n_3 \qquad \{10\}$$

Note that u_i is the control input (motor torque or current) if the i-th roller is driven, otherwise it is zero. The dancer roller translational dynamics is given by

$$M_d \ddot{x}_d = u_d - t_{24} - t_{25}. \qquad \{11\}$$

Note that since the length of the spans adjacent to the dancer roller (roller number 25) varies with dancer translational motion, the tension governing equations in these spans are given by:

$$\dot{t}_{24} = \frac{EA}{x_d(t)}(v_{25} - v_{24} + \dot{x}_d) + \frac{1}{x_d(t)}(t_{23}v_{24} - t_{24}v_{25} - t_{24}\dot{x}_d); \qquad \{12\}$$

$$\dot{t}_{25} = \frac{EA}{x_d(t)}(v_{26} - v_{25} + \dot{x}_d) + \frac{1}{x_d(t)}(t_{24}v_{25} - t_{25}v_{26} - t_{25}\dot{x}_d); \qquad \{13\}$$

2.4 Module 4 Governing Equations

Assuming that there are n_4 rollers in Module 3, the governing equation for web velocity on the rollers and web tension in spans are given by:

$$\dot{v}_i = \frac{R_i}{J_i}\tau_{fi} + \frac{R_i^2}{J_i}(t_i - t_{i-1}) + \frac{R_i}{J_i GR_i}u_i; \quad i = n_1 + n_2 + n_3 + 1 : n_1 + n_2 + n_3 + n_4 \qquad \{14\}$$

$$\dot{t}_i = \frac{EA}{L_i}(v_{i+1} - v_i) + \frac{1}{L_i}(t_0 v_1 - t_1 v_2); \quad i = n_1 + n_2 + n_3 + 1 : n_1 + n_2 + n_3 + n_4 \qquad \{15\}$$

Although the target unwind for developing the computer program was the one shown in Fig. 1, the user can specify the number of rollers in each module including the number of rollers on the festoon carriage.

3 MODEL SIMULATION PROGRAM DEVELOPMENT

The program is divided into the following three parts:

1. Inputs: Entering input variables into MATLAB workspace and calculation of additional variables that are required by the model.

2. Governing equations and control systems: Line simulation that includes dynamic models of the web and web handling elements, controllers, and program sequencing.

3. Outputs: Output from model simulations that includes evolution of all the key variables: span tensions, roller velocities, roll diameter, festoon position, etc.

The model simulation consists of two files, a master Matlab script file and a Simulink model file that has the governing equations for all the modules. The master script file is used to prepare the input parameters, develop initial conditions, and derive line operating conditions for running the model simulation using the Simulink model file. The parameters for the Simulink model are obtained from an input data file which can be created using a Graphical User Interface (GUI) or other means (or MS Excel to create the input data file). All the input parameters are converted into SI units for model simulation. The Simulink model contains several layers of blocks. The top layer contains the overall layout of the unwind and follows the description of the four modules discussed earlier.

The simulation sequencing block and the blocks corresponding to the dynamic equations for each module can be found in the top layer of the Simulink model (see Fig. 2). Each of these module blocks is preceded by a block that implements the control algorithm. The outputs are festoon reference, the simulation time at the beginning of zero speed splice, and spindle reference velocity profile. There is feedback from the unwind roll controller to the simulation sequence block because the web velocity coming off the material roll at the beginning of deceleration of the roll is unknown a priori; the outer festoon position loop provides correction to the spindle reference velocity and this correction must be communicated to the simulation sequence to provide reference profile during deceleration of the spindle. The outputs of the sequencing block are the inputs to the spindle motor controller.

Implementation of two specific blocks in the Simulink model warrant a special mention as it could be done in a number of ways. Several options were tried and the option that was actually implemented provided the best results in terms of simplicity and accuracy of simulation results to the observed line behavior. This is related to how to deal with simulation continuation during transfer from the spindle containing the expiring roll to the spindle containing the new roll. The two blocks in question are the blocks entitled "Unwind Roll Control" and "Dynamics from Unwind Roll to Span Before Festoon First Roll (Module 1)". The layer behind the "Unwind Roll Control" block contains the blocks and code related to the selection of spindles. Spindle A control loop corresponds to the expiring roll and is active until the end of the splice. Spindle B control loop corresponds to the new roll. During the splice, Spindle A velocity reference is set to zero. Once the splice time (input parameter) is elapsed, Spindle B is activated and accelerated to the reference speed as per the profile provided by the simulation sequence block. The second aspect is the radius calculator. Implementation of the dynamic equations for Module 1 requires calculation of radius and transfer from expired roll radius to the full roll radius. Just before the end of the splice time (after 75% of the splice time is elapsed), the radius is initialized to the new roll radius.

6

Figure 2 – Unwind SIMULINK Block Diagram Outline

3.1 Input Variables

In this section we will discuss the answers to two basic questions: What are the input variables? How do we enter and populate them into the MATLAB workspace? The input variables to the simulation model are

1. Web geometric and mechanical properties: width, thickness, modulus, and density.

2. Line operating conditions: reference speed, reference tension, festoon fill rate, festoon run and splice heights, spindle acceleration/deceleration profiles, splice time and web wrap angles on rollers.

3. Primitive element parameters:

   (a) Motor parameters: gear ratio, base speed, horsepower, controller gains, and speed filter corner frequencies.

   (b) Festoon parameters: festoon full height, carriage mass, number of rollers, and roller mass, inertia, diameter, and length.

   (c) Roller/Span parameters: roller diameter, span length, roller inertia, static and dynamic coefficient of friction between web and roller surface, and bearing friction.

   (d) Material roll parameters: roll OD, roll density, expired roll OD.

   (e) Linear dancer parameters: mass, cylinder diameter, and friction.

Two ways are provided to enter the input variables into Matlab work space: a Graphical User Interface (GUI) and directly into an input cell structure in the Matlab master script file. The main GUI contains the basic input parameters: reference line speed, web tension, web modulus, thickness, width, festoon fill rate, spindle acceleration and deceleration values for the splicing operation. It also contains two parameters pertaining the festoon air drag model included in the model simulation equations, an option to turn the air drag on or off and the air drag coefficient that is used in the air drag model; these will be later described in the model description and implementation section. The basic input parameters entered into this panel are stored in a cell structure which is saved to a MATLAB data file. In addition to the input parameters, the main GUI can be used to produce basic output plots and contains help reports and a description on how to determine the splicing parameters.

The main GUI also provides access to a back-end GUI. The back-end GUI can be used to input all the other line parameters and operating conditions. The input parameters can be entered in seven different panels: Motor Parameters, Festoon Parameters, Roller/Span Parameters, Simulation Time Parameters, Material Roll Parameters, Linear Dancer Parameters, and Number of Idlers in Modules. The parameters entered in all the panels are stored in a Matlab main data file. British units are used for entering the parameters except for mass and density. Units are clearly specified for each parameter and must be entered in those units.

3.2 Model Outputs

The outputs from the model simulation are: (1) all span tensions; (2) web velocities on all rollers; (3) material roll diameter; (4) carriage position; (5) dancer position; (6) controller outputs; and (7) resonant frequencies due to idlers and spans in the festoon. After the conclusion of a simulation, all the parameters and variables, both inputs and outputs, are saved to a data file. This file can be renamed and saved to be loaded in Matlab workspace later for plotting and analysis. The main GUI can be used to plot the basic outputs, such as span tensions and web velocities from the four modules as well as material roll diameter, carriage position, and festoon resonant frequencies as a function of span lengths.

4 DETERMINATION OF UNWIND SPLICING PARAMETERS

The splicing operation consists of four phases: (1) Festoon fill, (2) deceleration of the expiring roll, (3) clamp and dwell time for splicing, and (4) acceleration of the new roll. A typical festoon position profile as a percentage of full height is shown in Figure 3.
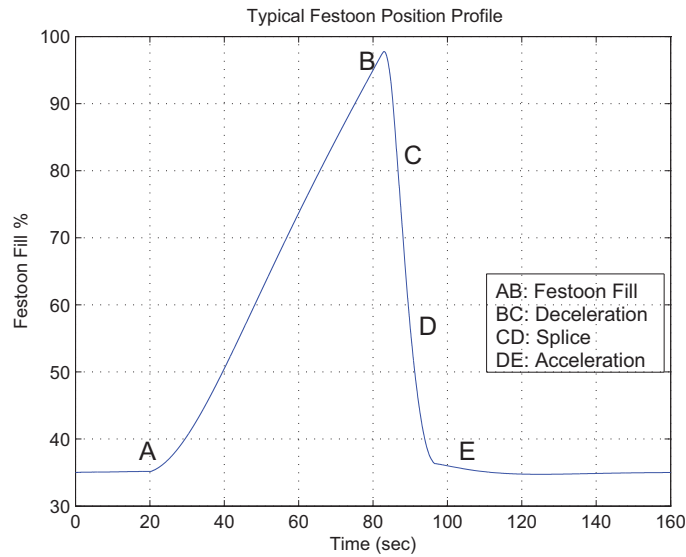
Figure 3 – Festoon fill position profile

Web length released from festoon

- **Splice:** The decrease in web length in the festoon during clamp and dwell time is given by

$$W_{cd} = \frac{v_p t_{cd}}{60}. \qquad \{16\}$$

- **Acceleration:** The time required for acceleration of the new roll from zero

speed to the nominal speed is given by

$$t_a = \frac{v_p}{a_s} \qquad \{17\}$$

The decrease in web length in the festoon during this time is the web length released to the process minus the web length gained from the new roll, which is given by

$$W_a = \frac{v_p t_a}{60} - \frac{1}{2}\frac{v_p t_a}{60} = \frac{v_p^2}{120 a_s}. \qquad \{18\}$$

- **Deceleration:** Due to the festoon fill operation, the web speed off the unwind roll at the beginning of deceleration is more than the nominal web speed; let this speed be $\beta_f v_p$ with $\beta_f > 1$. Therefore, for deceleration from βv_p to zero, there are two scenarios:

  1. Deceleration from $\beta_f v_p$ to v_p – festoon is filling. The amount of web length accumulated in the festoon during this period is given by

  $$W_{du} = \frac{1}{2}\frac{(\beta_f - 1)v_p}{60}t_{du} = \frac{(\beta_f - 1)^2 v_p^2}{120 d_s}. \qquad \{19\}$$

     where $t_{du} = (\beta_f - 1)v_p/d_s$ was used to obtain the last expression.

  2. Deceleration from v_p to zero – festoon is emptying. The amount of web length released from the festoon during this period is given by

  $$W_{dd} = \frac{v_p^2}{120 d_s}. \qquad \{20\}$$

Therefore, the net decrease in web length in the festoon during deceleration is given by

$$W_d = W_{dd} - W_{du} = \frac{(1 - (\beta_f - 1)^2)v_p^2}{120 d_s} \qquad \{21\}$$

The quantities W_{cd}, W_a and W_d as a percentage of the total festoon stroke are given by

$$y_{cd} = \frac{v_p t_{cd}}{60}\frac{100}{2NS_f}, \qquad \{22\}$$

$$y_a = \frac{v_p^2}{120 a_s}\frac{100}{2NS_f}, \qquad \{23\}$$

$$y_d = \frac{(1 - (\beta_f - 1)^2)v_p^2}{120 d_s}\frac{100}{2NS_f}. \qquad \{24\}$$

Maximum festoon fill height

The maximum height attained by the festoon as a percentage of total fill height is given by

$$y_m = y_f + \frac{(\beta_f - 1)^2 v_p^2}{120 d_s}\frac{100}{2NS_f}. \qquad \{25\}$$

Computation of the roll diameter at the beginning of festoon fill

The length of material in the roll between diameters D_{ex} and D_{fs} is given by

$$W_1 = \frac{\pi}{12}(D_{ex}+2h) + \frac{\pi}{12}(D_{ex}+4h) + \frac{\pi}{12}(D_{ex}+6h) + \cdots + \frac{\pi}{12}(D_{ex}+2nh)$$

$$= \frac{\pi}{12}nD_{ex} + \frac{\pi}{12}2h(1+2+3+\cdots+n)$$

$$= \frac{\pi}{12}nD_{ex} + \frac{\pi}{12}\frac{2hn(n+1)}{2} \quad\quad \{26\}$$

where n denotes the number of layers of web material between the diameters D_{ex} and D_{fs}, which is given by

$$n = \frac{(D_{fs}-D_{ex})}{2h}.$$

Substitution of n and simplification gives

$$W_1 = \frac{\pi}{48h}\left(D_{fs}^2 + 2hD_{fs} - D_{ex}^2 - 2hD_{ex}\right) \quad\quad \{27\}$$

Figure 4 shows a typical profile of web velocity off the material roll during a
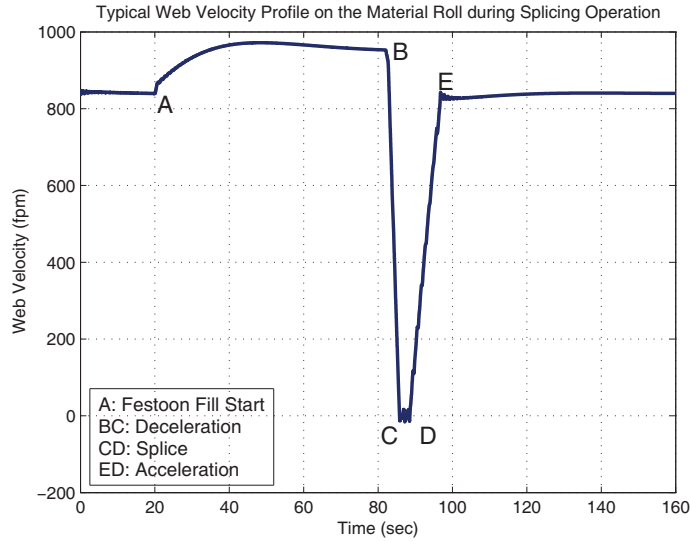
Figure 4 – Unwind web velocity profile

splicing operation. The web length released from the expiring roll from the beginning of festoon (denoted by "A") fill to stoppage of the roll (denoted by "C") can be obtained by integrating the velocity profile function from A to C. It is difficult to obtain a functional representation for the velocity profile from A to C since it is a function of outer position loop controller parameters and festoon position feedback. The sum of the web length stored in the festoon during festoon fill and web length released to the process is precisely the web length released from

the expiring roll from A to C. This sum is given by

$$W_2 = \frac{(y_f - y_s)2NS_f}{100} + \frac{v_p}{60}\frac{(y_f - y_s)}{v_f} + \frac{\beta_f^2 v_p^2}{120 d_s} \qquad \{28\}$$

where the first term in the right side is the material storage in the festoon during festoon fill and deceleration, the second term is the amount of material released to the process during festoon fill at v_f %/s and the third term is the amount of material released to the process during the part of deceleration where unwind velocity goes from .

Since W_1 must be equal to W_2, equating the above two expressions, we have the following equation for the roll diameter at the beginning of the festoon fill:

$$D_{fs}^2 + c_1 D_{fs} - c_0 = 0 \qquad \{29\}$$

where

$$c_0 = D_{ex}^2 + 2hD_{ex} + \frac{48h}{\pi}W_2,$$

$$c_1 = 2h.$$

The positive solution of equation {29} gives the "Start Fill Diameter." Since the coefficient $c_1 << c_2$, a reasonable approximation of the "Start Fill Diameter" that can be easily coded into any real-time implementation program is given by

$$D_{fs} = \sqrt{c_0} = \sqrt{D_{ex}^2 + 2hD_{ex} + \frac{48h}{\pi}W_2}. \qquad \{30\}$$

The sample plots shown in Figures 5, 6 and 7 were obtained using the following parameter values: $t_{cd} = 2.8$ seconds; $h = 0.0035$ inches; N=8; $S_f = 11.7083$ feet; $D_{ex} = 8.4$ inches; $\beta_f = 1.15$; $v_f = 1$ %/s.

5 MODEL SIMULATIONS

Model simulation data obtained for line speeds of 1200 FPM and 850 FPM are shown in Figures 8 through 15. The plots show that the simulation model is able to predict line speeds as well as line tensions. Block diagrams of the Pull Roll 1 and Spindle/Festoon Control Systems are provided in Figures 16 and 17, respectively.

6 CONCLUDING REMARKS

The described Matlab/Simulink model can be used for selection of transport and splicing parameters as well as equipment redesign/design of an existing/new unwind. The governing equations for the unwind as programmed into the Matlab/Simulink program predict the typical behavior observed on production unwinds. Model simulations were conducted for a number of scenarios with speeds ranging from 650 fpm to 1300 fpm, and the results seem to be as predicted. One key conclusion that we can deduce from the model simulations is that the line behavior during the splicing operation is dependent on how the acceleration and

deceleration profiles are chosen based on the line speed. For example, acceleration of the new roll must be chosen such that the festoon is closer to the run height when the new roll reaches line speed; this allows for smooth transition from speed loop only during the beginning of new roll acceleration to engaging the festoon position loop. The festoon position outer loop engagement criteria should be selected appropriately to facilitate this smooth transition. This issue was also tested and verified during experimentation on a production unwind.

Although the governing equations in the model assume that the webs are elastic, it can reasonably predict the trends of the key variables (tensions, velocities) during an unwind splice operation which includes festoon fill, deceleration of the expiring roll, splicing, and acceleration of the new roll to the steady line speed. A simple constitutive equation (linear elastic) between web strain and web tension was used to determine the governing equation for web tension based on the governing equation for web strain. If one wishes to include a simple linear or nonlinear viscoelastic constitutive equation (a first-order ODE between web strain and web tension), then the tension span equations in the basic model can be easily modified; for each span there will be an additional first-order ordinary differential equation.

REFERENCES

1. J. J. Shelton, "Dynamics of a web accumulator," in Proceedings of the Fifth International Conference on Web Handling, Stillwater, Oklahoma, 1999.

2. P. R. Pagilla, E. O. King, L. H. Dreinhoefer, and S. S. Garimella, "Robust observer-based control of an aluminum strip processing line," IEEE Transactions on Industry Applications, vol. 36, no. 3, pp. 865–870, 2000.

3. P. R. Pagilla, S. S. Garimella, L. H. Dreinhoefer, and E. O. King, "Dynamics and control of accumulators in continuous strip processing lines," IEEE Transactions on Industry Applications, vol. 37, no. 3, pp. 934–940, 2001.

4. P. R. Pagilla, I. Singh, and R. V. Dwivedula, "A study on control of accumulators in web processing lines," Journal of Dynamic Systems, Measurement, and Control, vol. 126, pp. 453–461, 2004.

5. P. R. Pagilla, R. V. Dwivedula, and N. Siraskar "Decentralized control of web processing lines," IEEE Transactions on Control Systems Technology, vol. 15, no. 1, pp. 106–117, 2007.

6. N. J. Michal, "Web tension in an accumulator and industry needs for the future," in Proceedings of the Tenth International Conference on Web Handling, Stillwater, Oklahoma, 2009.

7. J. J. Shelton, "Improvement of control of a web accumulator," in Proceedings of the Tenth International Conference on Web Handling, Stillwater, Oklahoma, 2009.

8. P. R. Pagilla and Y. Diao, "Resonant frequencies in web process lines due to idle rollers and spans," Journal of Dynamic Systems, Measurement, and Control, vol. 133, 2011.

9. D. Kuhm, D. Knittel, and M.-A. Bueno, "Robust control strategies for an

electric motor driven accumulator with elastic webs," <u>ISA Transactions</u>, vol. 51, no. 6, pp. 732–742, Nov. 2012.

10. P. R. Pagilla and P. R. Raul, "Design of control systems to mitigate web tension oscillations," in <u>Proceedings of the 2014 AIMCAL Web Coating and Handling Conference</u>, Myrtle Beach, S. Carolina, 2014.

11. P. R. Raul and P. R. Pagilla, "Design and implementation of adaptive PI control schemes for web tension in roll-to-roll manufacturing," <u>ISA Transactions</u>, vol. 20, no. 3, June 2012.
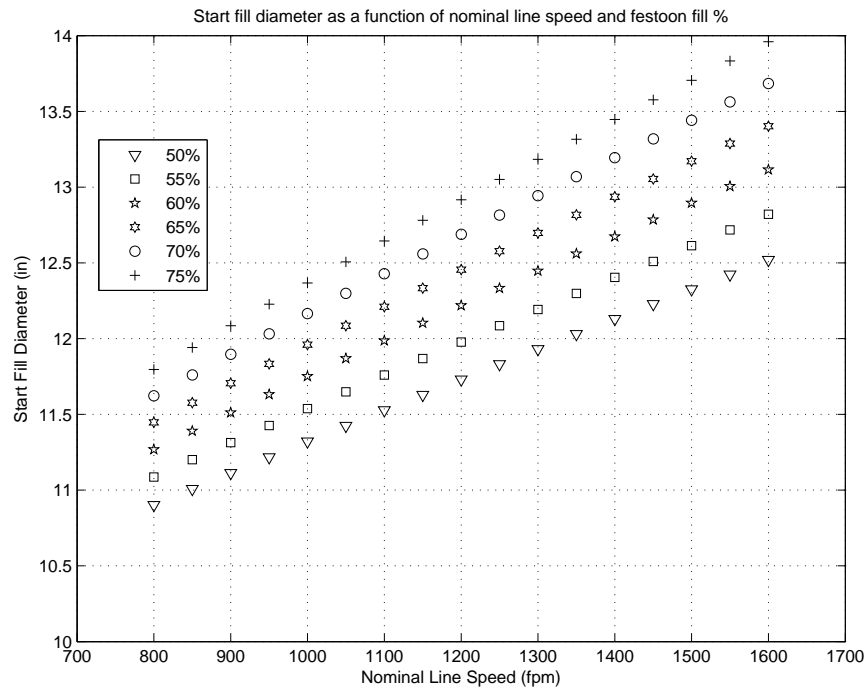
Figure 5 – Start Fill Diameter vs. Line Speed and Festoon Fill % (Expired Roll Diameter = 8.4 in)
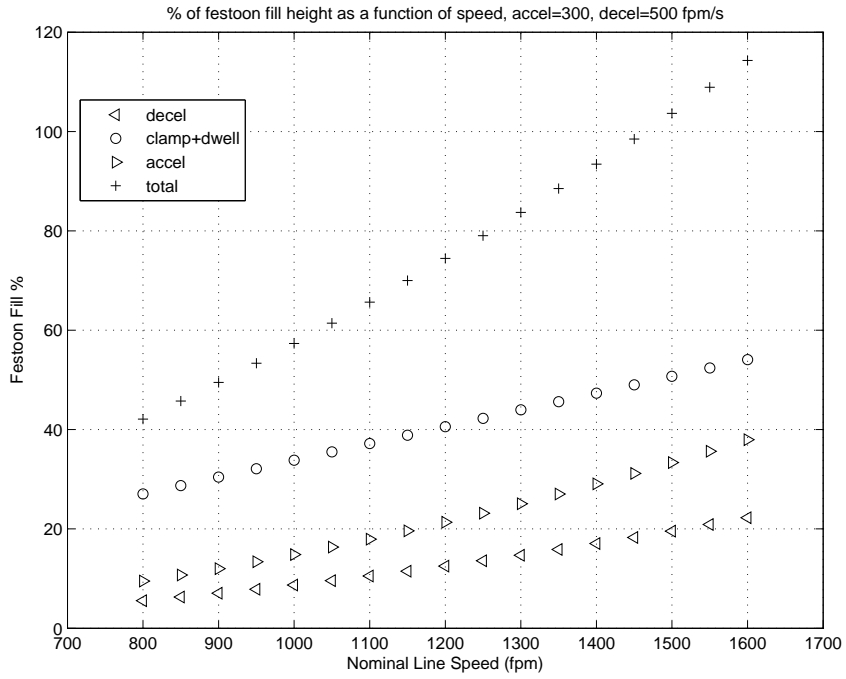
Figure 6 – Festoon Fill vs. Line Speed (accel = decel = 300 fpm/s)
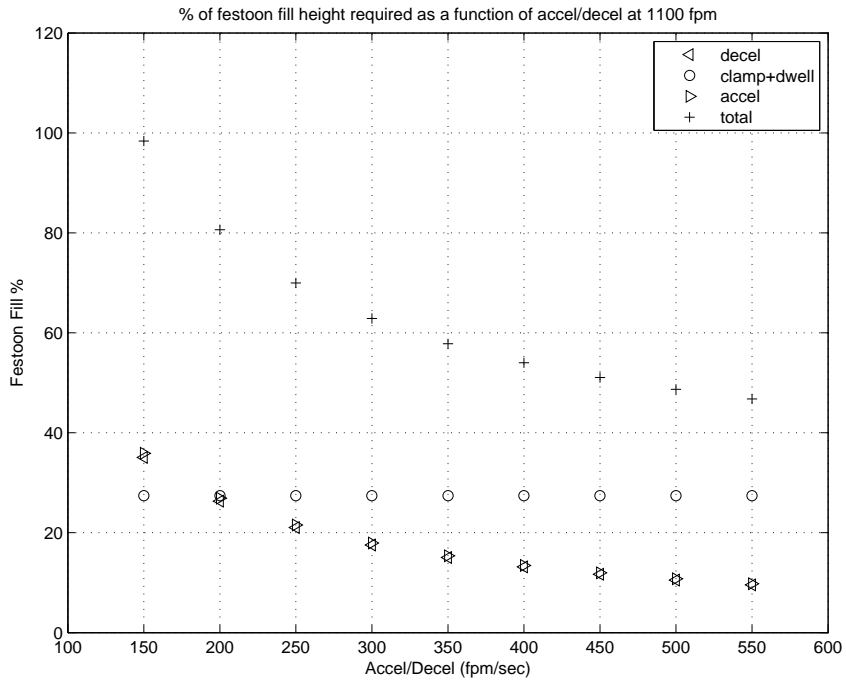
Figure 7 – Festoon Fill vs. Acceleration/Deceleration (line speed = 1100 fpm)
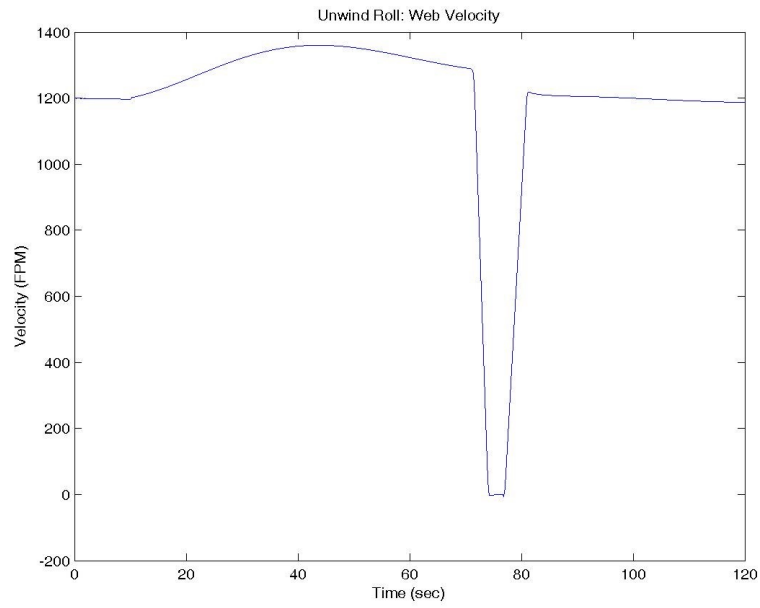
Figure 8 – Web Velocity on Spindle (Line speed=1200 fpm; Ds=500; As=300)
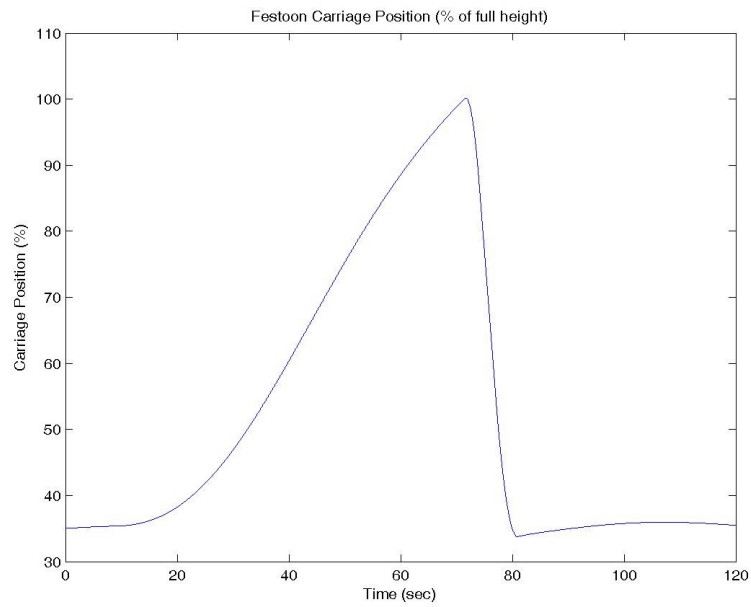
Figure 9 – Carriage Position (Line speed=1200 fpm; Ds=500; As=300)

16
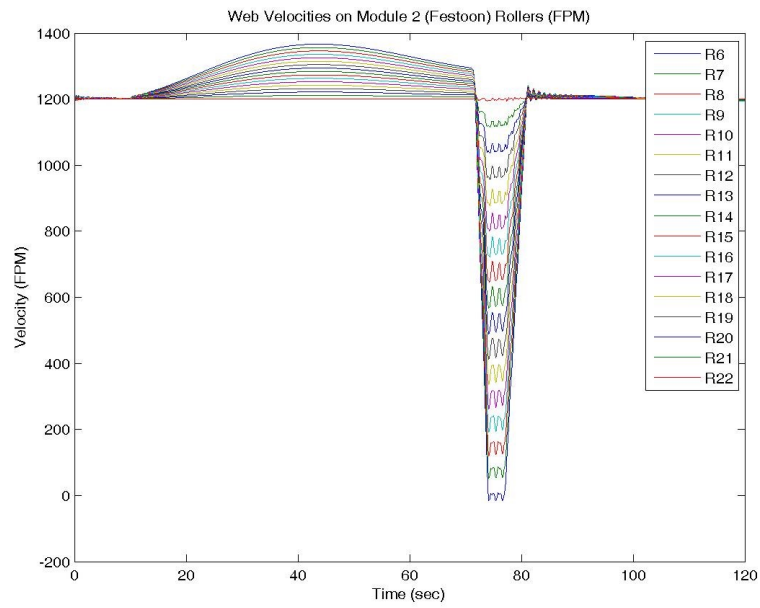
Figure 10 – Web Velocities on Festoon Rollers (Line speed=1200 fpm; Ds=500; As=300)
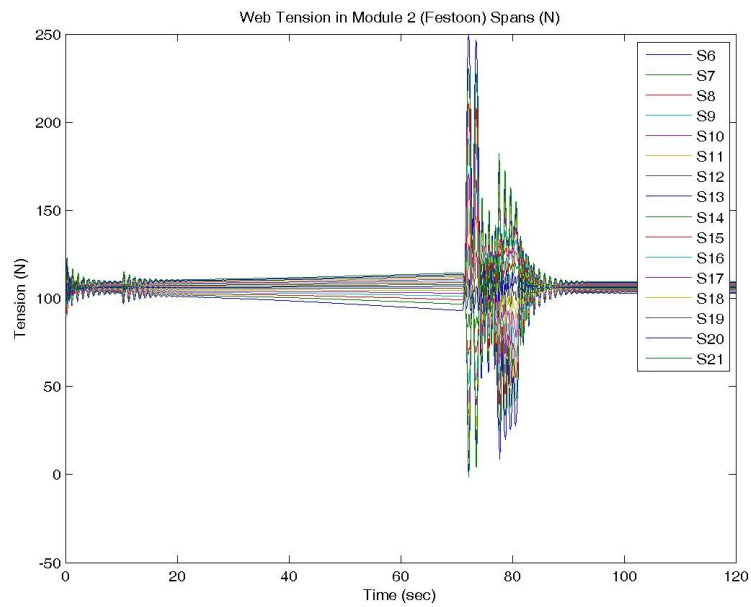
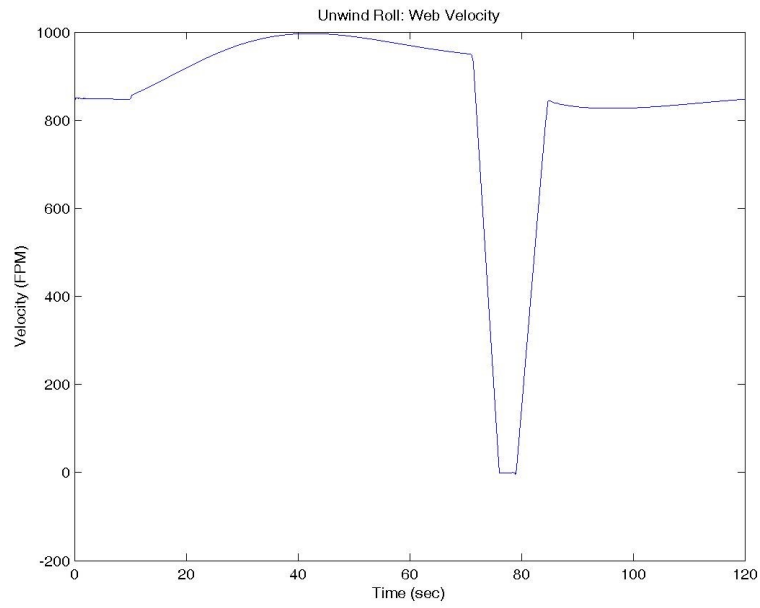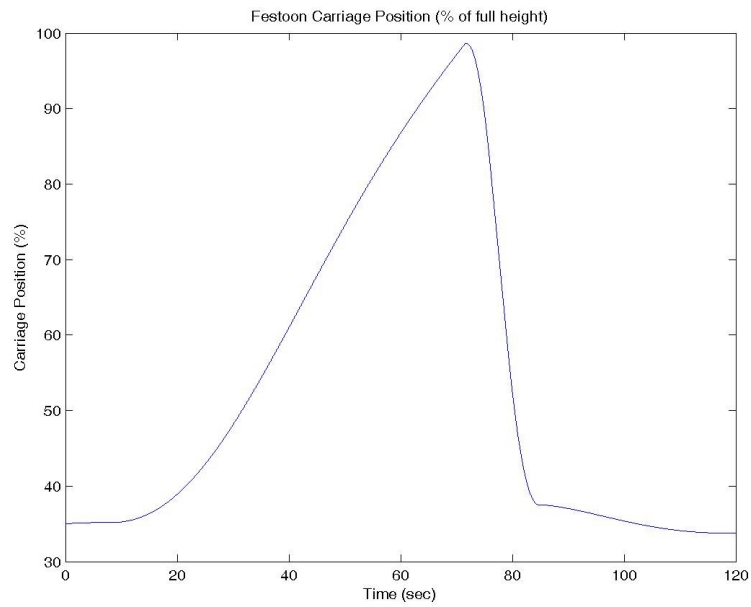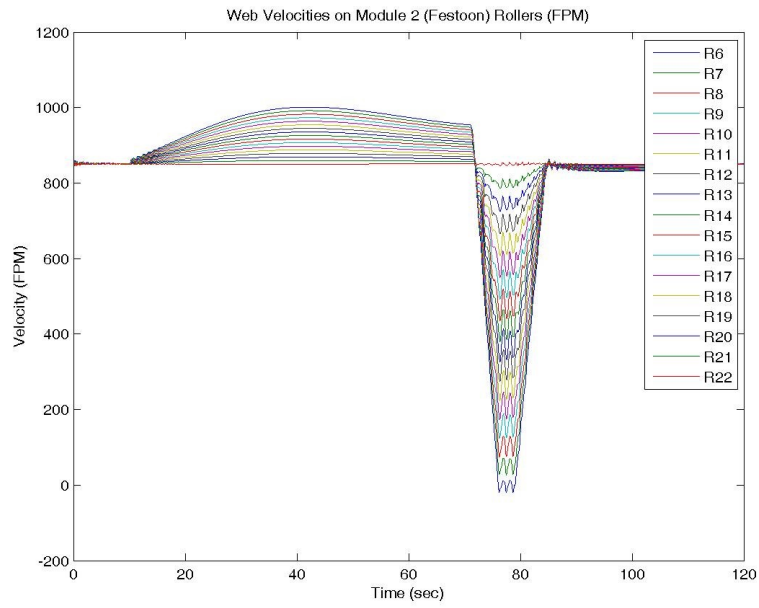Figure 11 – Web Tensions in Festoon Spans (Line speed=1200 fpm; Ds=500; As=300)

17

Figure 12 – Web Velocity on Spindle (Line speed=850 fpm; Ds=200; As=150)

Figure 13 – Carriage Position (Line speed=850 fpm; Ds=200; As=150)

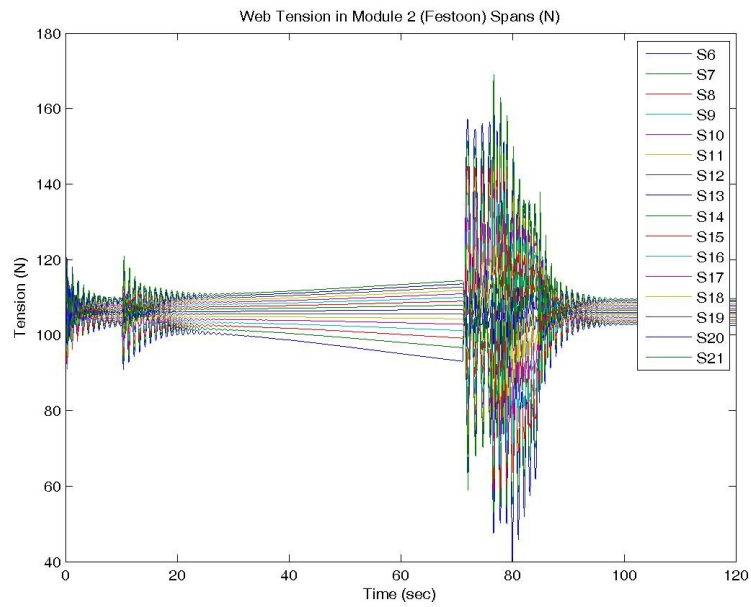Figure 14 – Web Velocities on Festoon Rollers (Line speed=850 fpm; Ds=200; As=150)

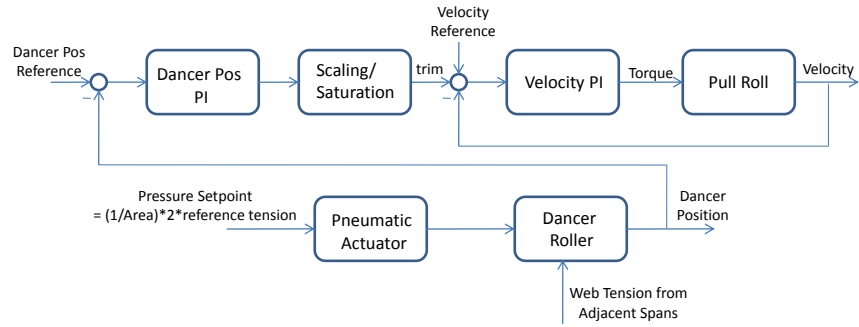Figure 15 – Web Tensions in Festoon Spans (Line speed=850 fpm; Ds=200; As=150)
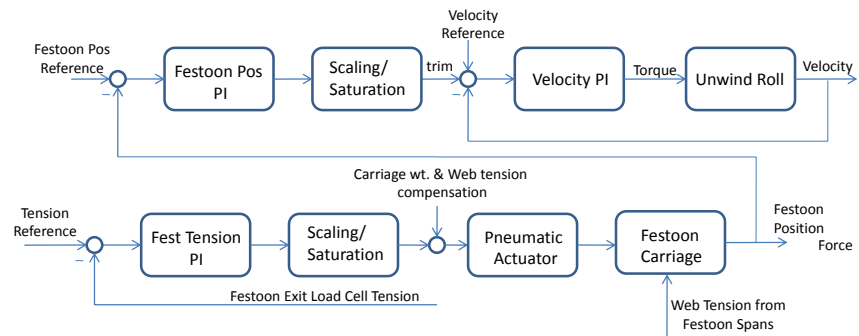
Figure 16 – Pull Roll 1 Control System

Figure 17 – Spindle and Festoon Control System