MODELING AND FREQUENCY RESPONSE OF WEB TENSION WITH A PENDULUM DANCER, AND COMPARISON OF LOAD-CELL AND DANCER BASED TENSION CONTROL SYSTEMS

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ABSTRACT

In web processing lines, web tension is typically regulated using an outer loop that provides a trim to the velocity reference of the inner velocity loop. The feedback signal for the outer tension loop is either a position signal from a dancer or tension signal from load cells mounted on a roller. Both these strategies are used extensively in the web processing industry, but a systematic analysis, based on mathematical models and experimental observations, on the benefits and limitations of the strategies is lacking. The paper will report two investigations. First, a model that describes the action of a pendulum dancer on web tension will be developed, and frequency response of web tension in the presence of the pendulum dancer will be discussed. Second, a comparison of tension control strategies based on force feedback from load cells and position feedback from dancer motion will be given.

NOMENCLATURE

A	:	Area of cross-section of the web
A_e	:	Area of cross-section of the pneumatic cylinder
E	:	Modulus of elasticity of the web material
F_p	:	Force due to air pressure
F_s	:	Force in the pneumatic cylinder spring
J	:	Inertia of the motor
J_i	:	Inertia of the i^{th} roller
J_p	:	Pendulum dancer inertia
L_i	:	Length of the ith web span
M	:	Disturbance amplitude
M_p	:	Mass of the pendulum dancer
R_i	:	Radius of the ith Roller

T_i	:	Web tension variation from the reference value in the i^{th} web span
V_i	:	Web velocity variation from the reference value on the i^{th} roller
b	:	Coefficient of bearing friction in the dancer
d	:	Diameter of the pendulum dancer roller
f_i	:	Coefficient of bearing friction in the i^{th} roller
g	:	Acceleration due to gravity
k	:	Pneumatic cylinder spring constant
k_p	:	Proportional gain in a PI controller
k_{rf}	:	Proportional gain reference
l	:	Length of the pendulum dancer
m	:	Mass of the roller
p	:	Air pressure in the pneumatic cylinder
s	:	Laplace variable
t	:	Time parameter
t_i	:	Web tension in the i^{th} web span
v_i	:	Web velocity on the i^{th} roller
w_{ld}	:	Lead frequency in a PI controller
y	:	Pneumatic cylinder spring displacement
z	:	Vertical distance to the center of mass
Θ	:	Pendulum dancer angle variation
$\Delta\alpha$	:	Variation in the angle of the dancer web span
α	:	Angle of the dancer web span
ν	:	Frequency (Hz)
θ	:	Pendulum dancer angle with respect to the vertical axis
ζ	:	Damping ratio of a second order system

Subscripts:

S	:	Related to the S-wrap roller
i	:	Span index, $i = 0, 1, 2, \ldots$
n	:	Idle roller number, $n = 1, 2, \ldots$
r	:	Related to reference value
u	:	Related to the unwind

INTRODUCTION

The model of a web section between two driven rollers containing a pendulum dancer differs from the one containing load cells mounted on an idle roller, even though the goal is to regulate tension in that section based on position feedback from the dancer or force feedback from the load cells. The thought process in using the position of the pendulum dancer as a measure of changes in web tension from its set point value is that any web tension variations can cause motion of the pendulum dancer which is reflective of changes in web tension. But since the pendulum dancer itself being a dynamical system with non-zero inertia around its pivot point, the motion of the dancer will affect web tension in adjacent spans. Discussion in this regard will be presented. Further, due to the motion of the dancer, the span lengths adjacent to the dancer are changing and this aspect will be incorporated into the modeling of web tensions in adjacent spans in the presence of a pendulum dancer.

The frequency response study gives insight into the benefits and limitations of using dancer and load cell rollers for tension control and relates the limitations to the accuracy of tension control systems. It also provides a means to verify whether the developed models predict observed experimental behavior. Dancer and load cell based tension control strategies will be discussed by providing model simulations and experimental results obtained on a large experimental web platform. The frequency response study gives insights into the benefits and limitations of using dancer and load cell rollers as feedback devices in developing tension control systems. The frequency response study may also facilitate design and implementation of efficient filters using statistical methods for better tension regulation.

The following specific studies were investigated and reported in this paper: Time domain and frequency response experiments were conducted for the unwind section which containing a pendulum dancer and load cell rollers. The time domain study corresponds to the evaluation of the dancer and load cell based control systems to regulate tension in the presence of speed changes of the web line, i.e. acceleration and deceleration. A controller normalization procedure that can be used to determine the gains of the dancer based control system from load cell based control system, and vice-versa, is discussed. The dancer and load cell control strategies are compared based on the frequency response experimental results. The performance improvement resulting from replacing the mechanical regulator with an electromechanical pressure regulator (EPR) in the pendulum dancer system is discussed. The use of the EPR ensures precise setting of air pressure inside the pneumatic cylinder. Experimental results with the EPR show that tension oscillations are reduced by precisely controlling the pneumatic cylinder pressure.

PENDULUM DANCER SYSTEM MODEL

A schematic of the pendulum dancer system considered in this paper is shown in Figure 1. The pendulum dancer system consists of the dancer roller which is free to rotate around a pivot point, the two idle rollers upstream and downstream of the pendulum dancer roller, and the two spans adjacent to the pendulum dancer roller. In the following the governing equations for pendulum dancer oscillatory motion, tension in the two adjacent spans, and the web velocity on the idle rollers will be presented together with the linearization of the nonlinear governing equations.

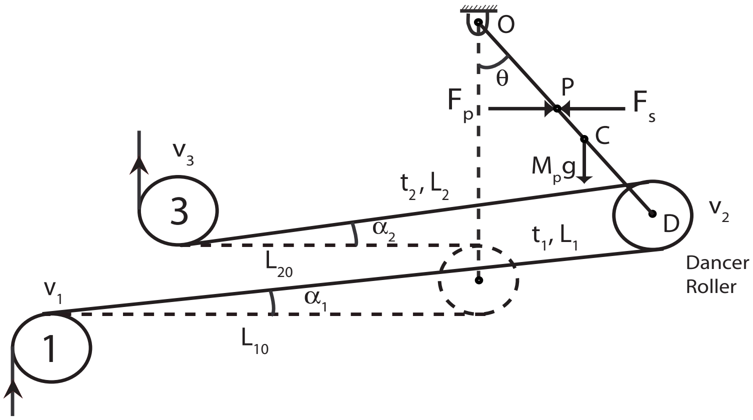

Figure 1 – Pendulum Dancer

Governing Equations

The governing equation for web tension in the i^{th} span whose length is varying with time is given by

$$\dot{t}_i = \frac{AE}{L_i}(v_{i+1} - v_i) + \frac{1}{L_i}(v_i t_{i-1} - v_{i+1} t_i) + \frac{1}{L_i}(AE - t_i)\dot{L}_i. \qquad \{1\}$$

Since the length of the spans adjacent to the dancer roller varies with the angular motion of the pivoted pendulum dancer, the above governing equation may be applied to obtain the following governing equations for tension in the two adjacent spans of the dancer roller:

$$L_1(t)\dot{t}_1 = AE(v_2 - v_1) + t_0 v_1 - t_1 v_2 + (AE - t_1)\dot{L}_1(t) \qquad \{2\}$$

$$L_2(t)\dot{t}_2 = AE(v_3 - v_2) + t_1 v_2 - t_2 v_3 + (AE - t_2)\dot{L}_2(t) \qquad \{3\}$$

where

$$L_1(t) = \frac{L_{10} + (l+d)\sin\theta}{\cos\alpha_1}, \quad L_2(t) = \frac{L_{20} + l\sin\theta}{\cos\alpha_2}$$

The web velocity dynamics on the i^{th} idle roller is given by

$$\dot{v}_i = \frac{R_i^2}{J_i}(t_i - t_{i-1}) - \frac{f_i}{J_i}v_i. \qquad \{4\}$$

The above equation for web velocity is derived under the assumption that there is no slip between the web and the surface of the roller, that is, the surface velocity of the roller is equal to the web velocity.

The equation that describes the dynamics of the angular motion of the pendulum dancer around the pivot point 'O' is given by

$$J_p\ddot{\theta} + b\dot{\theta} + M_p g z(\sin\theta) + F_s y - F_p y + t_2 l\cos(\theta - \alpha_2) + t_1(l+d)\cos(\theta - \alpha_1) = 0. \qquad \{5\}$$

The pneumatic cylinder force is given by $F_p = pA_e$ and the pneumatic spring force is given by $F_s = ky$.

Linearized equations

Linearization of the nonlinear equations is required to facilitate analysis of the resonant frequencies of the system. Of particular importance is the minimum resonant frequency, and how it behaves as a function of the physical parameters of the web and the associated web handling elements. A comprehensive study on frequency response analysis of a system of idle rollers can be found in [1]. The focus in this paper is on discussion related to the inclusion of a pendulum dancer as a feedback device, whose angular position variations lead to changes in web tension. The linearized equations may be used for this analysis. To linearize the equations around reference values the following perturbations are defined:

$$T_i = t_i - t_{ri}, \quad V_i = v_i - v_{ri}, \quad \Theta = \theta - \theta_r, \quad \Delta\alpha_i = \alpha_i - \alpha_{ri}. \qquad \{6\}$$

where t_{ri}, v_{ri}, θ_r, and α_{ri} are tension reference, velocity reference, pendulum dancer reference angle with respect to vertical axis, and web span angle, respectively. The variables T_i, V_i, Θ and $\Delta\alpha_i$ denote variations of tension, velocity, pendulum angle and web span angle from their reference values.

A prescribed reference web tension may be set by loading the arm of the pendulum dancer with a pneumatic actuator (see Figure 1); the pressure in the pneumatic cylinder is adjusted to obtain the required reference web tension. The reference pressure is selected such that the forced equilibrium position of the dancer is at zero degrees. Therefore, for this situation, the reference angle for the pendulum dancer is given by $\theta_r = \alpha_{r1} = 0$. Any deviations in web tension from its reference value result in oscillations of the pendulum dancer. Assuming the tension variations to be small, the angular motion of the dancer from the vertical is small, as a result both θ and α in the governing equations may be assumed to be small. With this small angle assumption, the sine and cosine terms may be linearized by using $\sin(\theta) \approx \Theta$ and $\cos(\alpha_i) \approx 1$. Under the assumption that the reference tension is constant and assuming the products of perturbation variables are negligible, the linearized equations for web tension in the adjacent spans of the dancer roller are given by

$$L_{10}\dot{T}_1 = AE(V_2 - V_1) + v_{r1}T_0 + V_1 t_{r0} - v_{r2}T_1 - V_2 t_{r1} + (AE - t_{r1})(l+d)\dot{\Theta} \qquad \{7\}$$
$$L_{20}\dot{T}_2 = AE(V_3 - V_2) + v_{r2}T_1 + V_2 t_{r1} - v_{r3}T_2 - V_3 t_{r2} + (AE - t_{r2})l\dot{\Theta}. \qquad \{8\}$$

The equation for web velocity perturbation on the roller is given by

$$\dot{V}_1 = \frac{R_1^2}{J_1}(T_1 - T_0). \qquad \{9\}$$

To linearize the governing equation for angular motion of the pendulum dancer around its pivot point, one has to also define the pressure perturbation from its reference value as $P = p - p_r$. Linearization of the nonlinear equations results in the following:

$$J_p\ddot{\Theta} = -b\dot{\Theta} - M_p gz\Theta - ky^2\Theta - T_2 l - T_1(l+d). \qquad \{10\}$$

State Space Model for the Unwind Section

The unwind section of the Euclid Web Line (EWL) (sketch shown in Figure 3) is considered for the frequency response study. The unwind section of

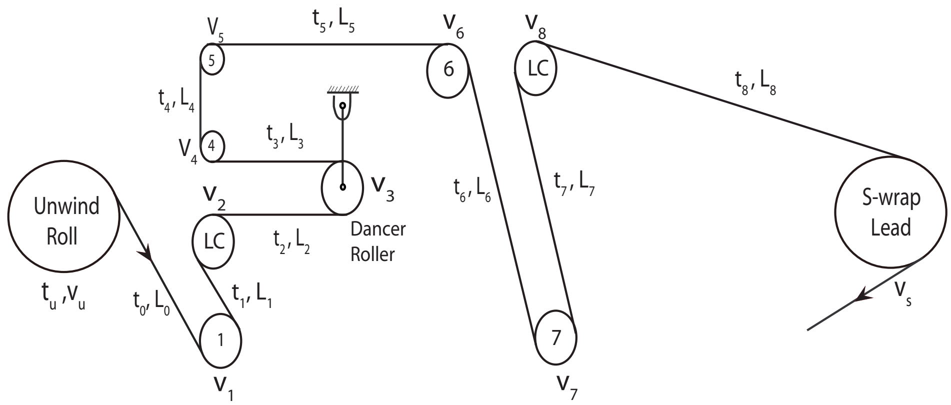

Figure 2 – Euclid Web Line Unwind Section

the EWL between the unwind roll and the S-wrap driven roller contains seven idle rollers including the dancer roller. Since there are many variables associated with the seven idle rollers, for presenting the state equations, a simplified section as shown in Figure 3 is considered.

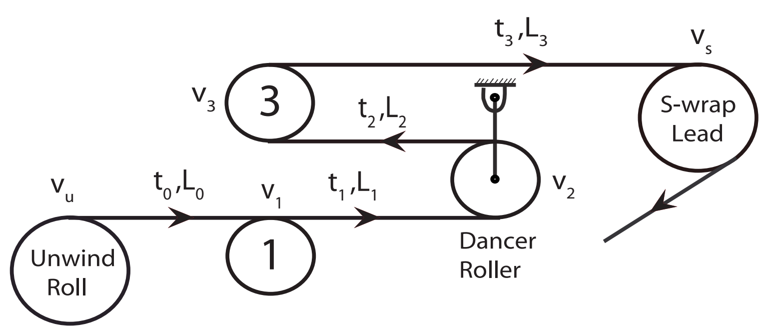

Figure 3 – Simplified Unwind Section with Pendulum Dancer

The linearized equations given in the previous section may be expressed in state space form by defining the state and input vectors as

$$X = \begin{bmatrix} T_0 & V_1 & T_1 & V_2 & \Theta & \dot{\Theta} & T_2 & V_3 & T_3 \end{bmatrix}^T, \quad U = \begin{bmatrix} V_u & V_s \end{bmatrix}^T. \qquad \{11\}$$

The linearized state space equation representing the unwind section is given by

$$\dot{X} = \mathbb{A}X + \mathbb{B}U. \qquad \{12\}$$

where

$$\mathbb{A} = \begin{bmatrix} -P_0 & K_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{m_1} & 0 & \frac{1}{m_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ P_1 & -K_1 & -P_1 & K_1 & 0 & (l+d)K_1 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{m_2} & 0 & 0 & 0 & \frac{1}{m_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{l+d}{J_p} & 0 & -S_p & -B_p & -\frac{l}{J_p} & 0 & 0 \\ 0 & 0 & P_2 & -K_2 & 0 & lK_2 & -P_2 & K_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{m_3} & 0 & \frac{1}{m_3} \\ 0 & 0 & 0 & 0 & 0 & 0 & P_3 & -K_3 & -P_3 \end{bmatrix} \quad \{13\}$$

$$\mathbb{B} = \begin{bmatrix} -K_0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & K_3 \end{bmatrix} \quad \{14\}$$

and

$$m_i = \frac{J_i}{R_i^2}; \quad P_i = \frac{V_r}{L_i}; \quad B_p = \frac{b}{J_p}; \quad K_i = \frac{AE - t_r}{L_i}; \quad S_p = \frac{ky^2 + M_p gz}{J_p}. \quad \{15\}$$

DANCER AND LOAD-CELL TENSION CONTROL SYSTEMS

Web tension behavior in the unwind section of the EWL with dancer and load cell feedback control strategies are studied separately. The goal is to assess the ability of each strategy to regulate tension. Comparative experiments are conducted in both time and frequency domain. The time domain experiments are performed with a step/ramp change in velocity while the frequency domain experiments are performed by injecting a sinusoidal velocity disturbances at the S-wrap roller. An approach to design equivalent PI tension controllers for both dancer and load-cell feedback control strategies is considered with normalizing gains. Controller normalization is required for a fair comparison of performance with the two strategies. In this section we discuss the control strategies and the controller normalization procedure.

S-wrap Roller Control Strategy

Figure 4 shows the speed control scheme for the S-wrap roller which is under pure speed regulation. The transfer functions for the motor/load inertia J of the S-wrap roller and the PI controller in frequency domain are given by

$$G_v(s) = \frac{1}{Js}, \; C_{sv}(s) = \frac{k_{ps}(s + \omega_{ld})}{s}. \quad \{16\}$$

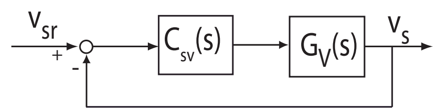

Figure 4 – S-wrap Control Strategy

where k_{ps} is proportional gain and ω_{ld} is the cut-off frequency. The closed-loop dynamics for the S-wrap roller is given by

$$\frac{v_s(s)}{v_{sr}(s)} = \frac{k_{rf}(s+\omega_{ld})}{s^2+k_{rf}s+k_{rf}\omega_{ld}}. \qquad \{17\}$$

where k_{rf} is reference proportional gain and ζ is damping ratio. Equation {17} is obtained by selecting $k_{ps} = Jk_{rf}$ with $k_{rf} = 15$ and $\omega_{ld} = \frac{k_{rf}}{4\zeta^2}$ with $\zeta = 1.1$.

<u>Unwind Roll Control Strategy</u>

The unwind roll is under a two-loop control strategy; the inner-loop provides speed regulation and the outer-loop provides a correction to the reference speed based on either tension feedback from a load-cell or dancer position feedback from a dancer. The unwind roll control strategy for the dancer and load-cell are shown in Figures 5 and 6, respectively. In the case of the dancer, the angular position of the dancer is sensed by a rotary variable differential transducer and the voltage signal is fed back to the outer-loop controller. The speed controller

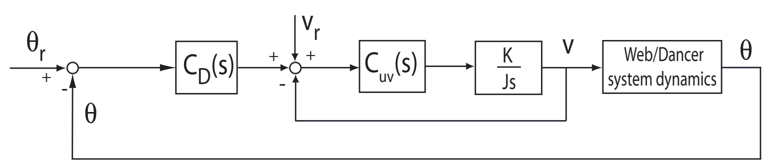

Figure 5 – Dancer Control Strategy

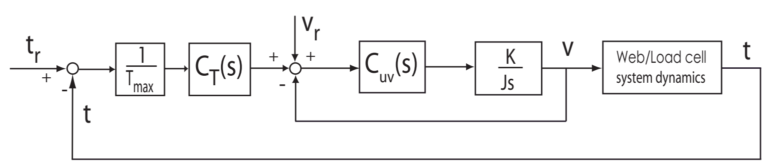

Figure 6 – Load Cell Control Strategy

for the unwind roll is expressed as

$$C_{uv}(s) = \frac{Jk_{rf}(s+\omega_{ld})}{s}. \qquad \{18\}$$

where $k_{rf} = 15$, $\omega_{ld} = \frac{k_{rf}}{4\zeta^2}$ with $\zeta = 1.1$.

The transfer function for the outer-loop with load-cell tension feedback is given by

$$C_T(s) = \frac{k_p(s+\omega_{ld})}{s}. \qquad \{19\}$$

where k_p is the proportional gain and ω_{ld} is the zero crossover frequency. The dancer position feedback control strategy is selected based on the controller normalization procedure discussed in the following section.

Controller Normalization

A basis for comparison of the performance of control systems with dancer and load-cell feedback requires some form of normalization of controllers. This is done by a way of determining the dancer controller gains based on the development of a relationship between dancer angular position and web tension under the assumption that the web is elastic. Figure 7 shows a sketch of the

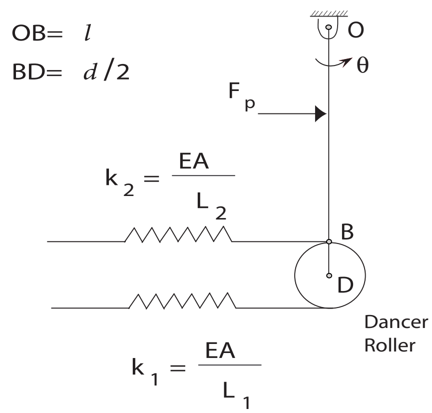

Figure 7 – Pendulum Dancer in Equilibrium

dancer in equilibrium state with corresponding spring constants for the web spans. The relationship between the dancer position and web tension is given by

$$T_1 + T_2 = k_1(l+d)\Theta + k_2 l\Theta = \left(\frac{EA}{L_1}\frac{\pi(l+d)}{180}\right)\Theta + \left(\frac{EA}{L_2}\frac{\pi l}{180}\right)\Theta. \qquad \{20\}$$

where Θ is in degrees. Assume that the change in span length due to dancer motion is negligible, $l \gg d$, and $T = T_1 = T_2$, the following relationship between tension variation T and angular position variation Θ can be obtained:

$$T = k(\Delta\theta l) = \left(\frac{EA}{L}\right)\left(\frac{\pi l}{180}\right)\Theta. \qquad \{21\}$$

Equation {21} represents the relationship between the dancer angular position and web tension under a static equilibrium condition. With this equation as the basis, one can determine a controller for the dancer that is equivalent to the controller with load-cell feedback. Figure 8 shows how the outer-loop controller with dancer position feedback may be obtained based on an existing load-cell based tension controller. The load-cell based tension PI controller for the unwind

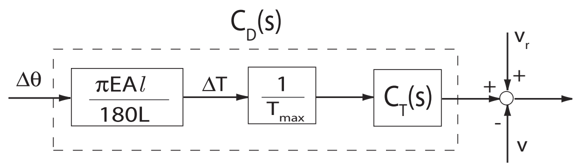

Figure 8 – Equivalent Dancer Controller

roll that is implemented on the EWL is given by

$$C_T(s) = \frac{12(s+0.1)}{s}. \tag{22}$$

Based on the above procedure, substitution of the parameter values $EA = 2800$ lbf, $l = 1.04$ ft, $L = 1.825$ ft, and $T_{max} = 50$ lbf, the equivalent dancer-based controller is

$$C_D(s) = \frac{4(s+0.1)}{s}. \tag{23}$$

The pendulum dancer typically has lower resonant frequencies than the load-cell; this will be verified later. So, the equivalent dancer controller may have to be tuned in some cases to provide adequate performance. In the case of the unwind section of the EWL, the dancer based controller given by equation {23} delivers very good tension regulation, which is discussed in the next section.

EXPERIMENTS AND MODEL SIMULATIONS

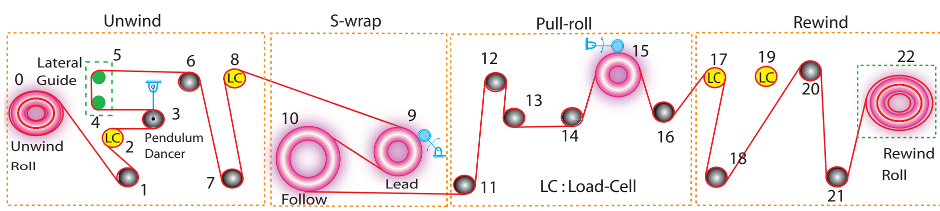

Figure 9 – Euclid Web Line Sketch

Figure 9 shows a sketch of the Euclid Web Line (EWL) experimental platform. The Euclid web line may be divided into four sections: the unwind section, the S-wrap section, the pull roll section, and the rewind section. The S-wrap rollers and the pull roll are under pure speed control to maintain the reference line speed. The unwind section contains load cells on rollers 2 and 8 which may be used to provide tension feedback for the unwind roll control system. For the load-cell based control strategy, feedback from load cells on roller 2 was used for the unwind roll as this roller is immediately upstream of the dancer roller. There are eight idle rollers in the unwind section from the unwind roll to the S-wrap rollers. The radius and inertia of each idle roller are 0.125 ft and 0.003 lbf ft s^2, respectively. The web span lengths for the unwind section of the EWL are given in Table 1.

L_0	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8
2.6	0.5	1.8	1.8	1.5	3.3	2.6	2.6	5.5

Table 1 – Web Span Length (ft) of Unwind Zone

Time Domain Experiments

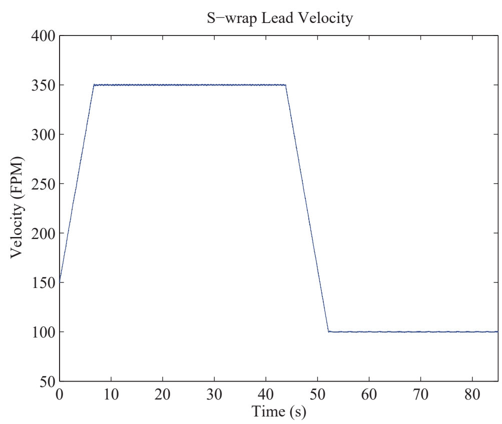

Figure 10 – S-wrap Speed Profile

Time domain experiments were conducted with the pendulum dancer by giving the reference speed profile for the S-wrap rollers as shown in Figure 10; the line is accelerated from 150 FPM to 350 FPM and decelerated back to 100 FPM. Web tension data was collected for the dancer and load-cell based tension control strategies. When using the load-cell based strategy the dancer motion around its pivot point is arrested so that the dancer roller simply acts as an idle roller. Three different sets of experiments were conducted for acceleration and deceleration of the line. In the first set, the dancer position feedback was used and tension data was collected from load cells on roller 8. In the second set load cell feedback on roller 2 is used and tension data was collected from the same load cells on roller 2. The third set is similar to the second set except that load cells on roller 8 are utilized as feedback to the unwind roll and for data collection. The controllers for the two strategies described by equations {22} and {23} are used. The unwind roll diameter is kept at 14 inches at the beginning of all experiments, ensuring uniform radius change in every set. The reference tension value of 20 lbf and the reference dancer angle were considered.

The tension data plots for the two strategies are shown in Figures 11 through 13. The calculated standard deviation indicates less tension variation with dancer based strategy when compared to the load-cell based strategy. The control system based on load-cell feedback is more sensitive to speed changes which results in higher tension fluctuations. For deceleration, when the S-wrap speed changes from 350 FPM to 100 FPM, the tension data plots are shown in Figures 11 through 13. Similar to the results with the acceleration of the line, it was found that the tension regulation performance was better with dancer feedback when compared with the load-cell feedback.

Frequency Response Experiments

The frequency response experiments were performed to verify if the minimum resonant frequency of the unwind section is predicted by the model. Experiments were performed for both the dancer and load-cell based control strategies. The S-wrap reference speed with a sinusoidal disturbance of the following form is chosen to obtain the frequency response:

$$v_r = v_{sr} + M(\sin 2\pi\nu_1 t + \sin 2\pi\nu_2 t + \ldots + \sin 2\pi\nu_n t) \qquad \{24\}$$

where $v_{sr} = 150$ FPM is the base reference velocity, $M = 5$ FPM is the amplitude, and ν_i is the frequency. Note that all the sinusoidal components are not implemented at once. A few frequencies are implemented at a time and the data are superimposed. In each experiment, tension behavior was investigated at 21 frequency points ranging from 0.5 Hz to 10 Hz. Model simulations were also conducted by injecting the same sinusoidal disturbance.

Model simulation and experimental results are shown in Figures 14 and 15. The resonant frequencies from model simulations agree with those from the experiments. In the case of the load cell feedback, there was a close match (minimum resonant frequency was 5 Hz). In the case of dancer feedback, the minimum resonant frequency from experiments was around 3.3 Hz and from model simulations was 3.5 Hz. The combined bode plot for dancer and load-cell feedback system is shown in Figure 16. The load-cell system has higher DC gain compared to dancer, since load-cell system is more stiff than dancer system. The FFT of the tension signal in the lower frequencies as shown in Figure 17 reveal that the dancer system can damp low frequency tension disturbances.

Evaluation of Electromechanical Pressure Regulator

A mechanical pressure regulator was used for supplying air to the pneumatic cylinder with required pressure in the experimental results shown previously. Since the mechanical regulator is an open loop system, it has limitations in regulating output pressure. The effects of back pressure and air flow variation can cause inconsistencies in the performance of pneumatic systems. Proportional regulators are used to eliminate these problems. In order to enhance the pendulum dancer system, the traditional mechanical regulator was replaced with an electromechanical pressure regulator (EPR) that contains an in built proportional controller. With mechanical type regulators, the pressure set point is manually adjusted by a control knob. There is no mechanism to monitor the error between the setpoint value and the actual value of the output pressure. By using the EPR, the output pressure is continuously measured and is adjusted to the setpoint value. The EPR has many other advantages over the traditional mechanical type regulator in terms of fast response time and good linearity. The EPR's output pressure can be set manually on the device panel or by an external voltage signal through a real-time system. The EPR is integrated into the Rockwell controller on the EWL and the output pressure now can be set through a program in ControlLogix. The chosen EPR has an output pressure range of 0 to 150 psi corresponding to set value input signal of 0 to 10 V.

To evaluate the performance of the EPR, time domain and frequency domain experiments were conducted and compared to the earlier results based on the mechanical type pressure regulator. The same setup was used for both experiments. Comparison of the results show that with EPR the tension variations are reduced by a considerable amount. This can be observed by comparing the frequency response results with the EPR shown in Figure 19 and those with the mechanical regulator as shown in Figure 14. Time domain experimental results indicate similar conclusions. Comparing the acceleration and deceleration plots 18 with 11 show reduction in standard deviation of web span tension. The pendulum dancer torque balance variational equation {10} reveals that any pressure variation in the pneumatic cylinder from the set point causes dancer angle fluctuations which can cause oscillations in web tension. Inclusion of the EPR did not affect the location of the resonant frequencies in the frequency range used for testing.

SUMMARY AND CONCLUSION

A model was developed for the pendulum dancer system. The ability of the developed model to predict resonant frequencies was verified by performing frequency response experiments. Time and frequency domain experiments were performed for two control strategies, an outer-loop tension controller based on the dancer position feedback and the other based on tension feedback from load cells mounted on a roller. The dancer position based feedback controller was normalized to the load cell based controller and tuned in order to reduce dancer oscillations. There was a close match in terms of the minimum resonant frequency (5 Hz) between model simulations and experiments based on load-cell feedback. For the dancer based feedback, the minimum resonant frequency was 3.5 Hz with the model and about 3.3 Hz from the experiments. Further, frequency response results also show that, in the low frequency range (0 to 3 Hz), tension variations with the dancer are much smaller compared to the load cell. The dancer was able to filter low frequency disturbances very well compared to the load cell. This was also evident from the time domain results where the line was accelerated and decelerated to evaluate the performance of the two control systems. It was also shown that by precisely regulating air pressure in the pneumatic cylinder with an electromechanical pressure regulator, the tension response can be improved.

ACKNOWLEDGEMENTS

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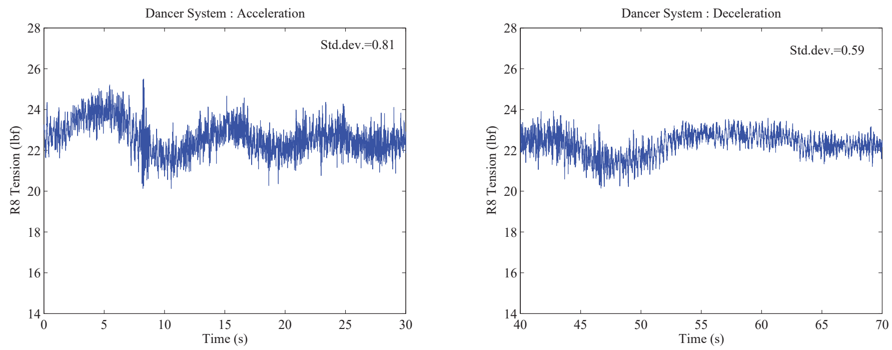

Figure 11 – Dancer Based Tension Control System: Left-Acceleration; Right-Deceleration

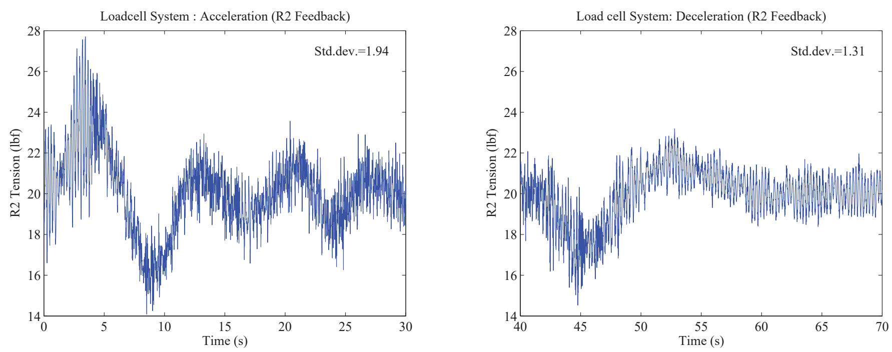

Figure 12 – Load-Cell Based Tension Control System (Load Cells on R2): Left-Acceleration; Right-Deceleration

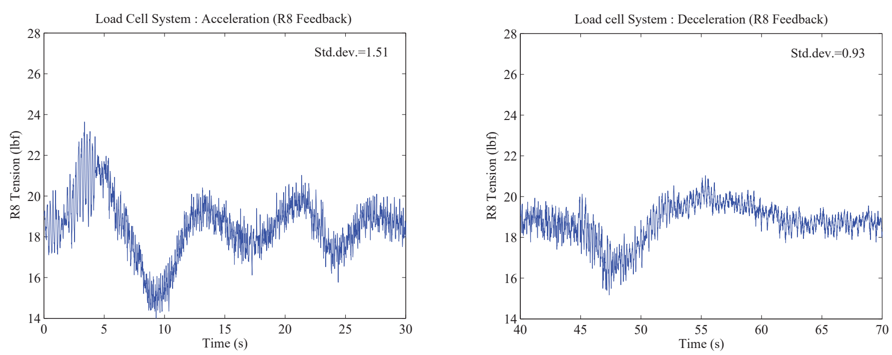

Figure 13 – Load-Cell Based Tension Control System (Load Cells on R8): Left-Acceleration; Right-Deceleration

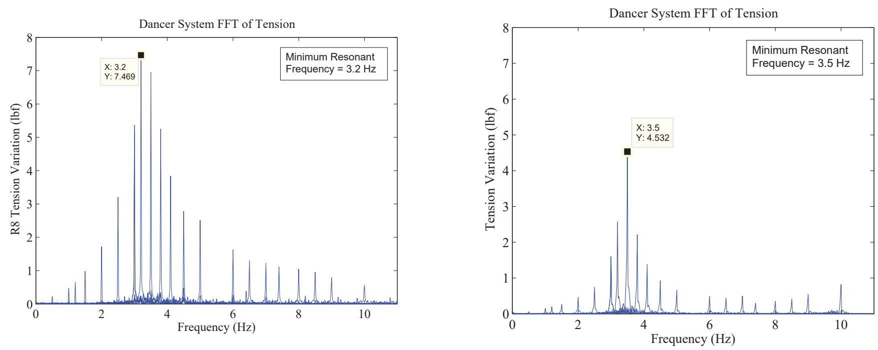

Figure 14 – Frequency Response Experiments and Model Simulations with Dancer Based Strategy

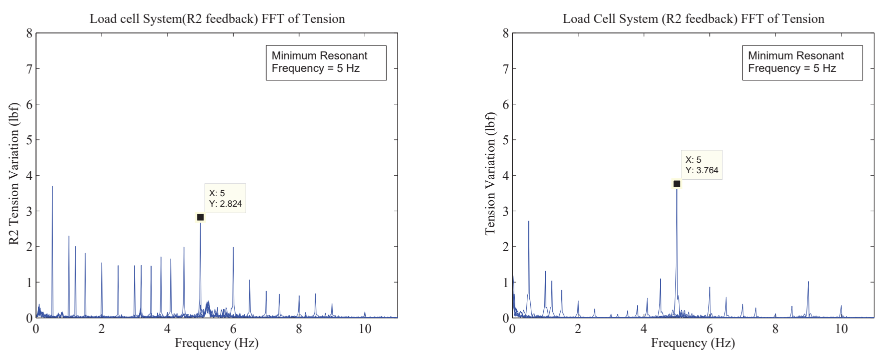

Figure 15 – Frequency Response Experiments and Model Simulations with Load-Cell Based Strategy

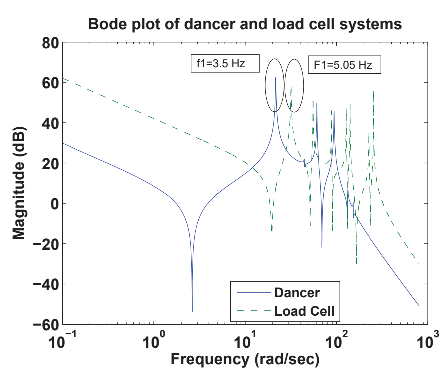

Figure 16 – Bode Plot:Dancer and Load-Cell Feedback System

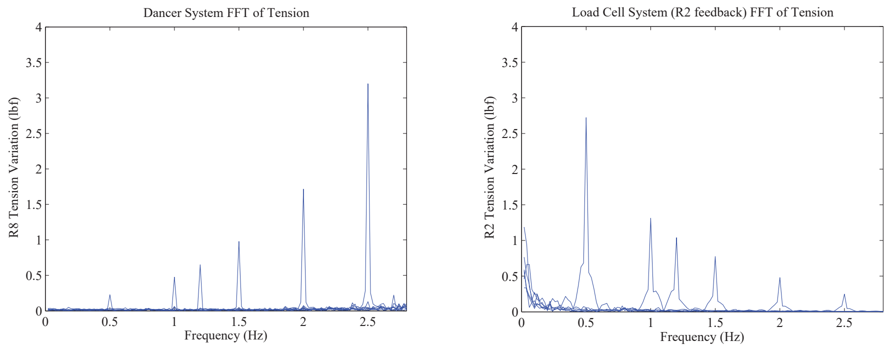

Figure 17 – Low Frequency Content in Tension Signal with Dancer and Load-Cell Based Strategies

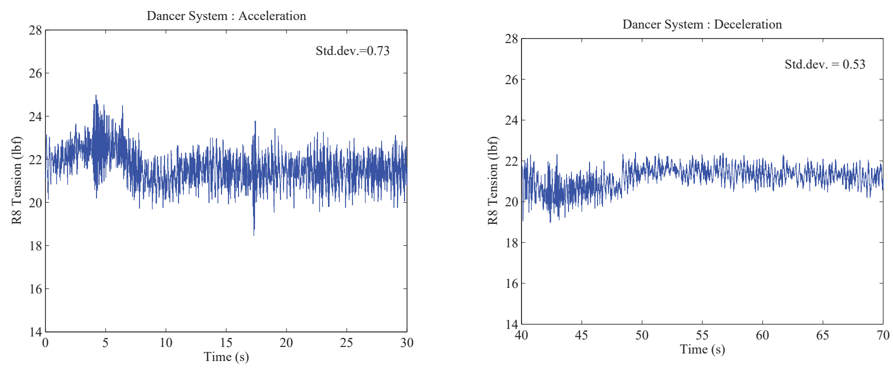

Figure 18 – Dancer Based Tension Control System (with Electro-Mechanical Pressure Regulator): Left-Acceleration; Right-Deceleration

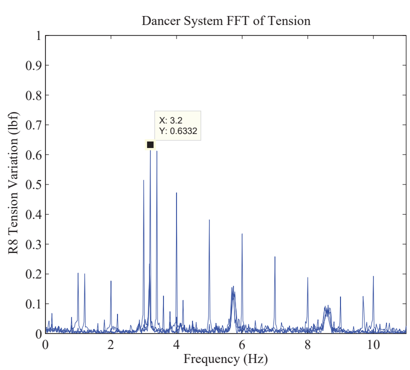

Figure 19 – FFT of Tension Data with EPR

Modeling and Frequency Response of Web Tension with a Pendulum Dancer, and Comparison of Load-Cell and Dancer Based Tension Control Systems

P. Raul & P. Pagilla,
Oklahoma State University, USA

Name & Affiliation	Question
Clarence Klassen, KlassEngineering	I wonder if you could comment on the velocity regulators.
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	We are using a velocity-based tension control system. The inner loop is velocity regulation and the outer loop is based on tension feedback and provides a correction to the velocity reference for the inner loop. The velocity regulators are proportional-integral type, and the proportional and integral gains are tuned for providing zero steady-state error to step and ramp references and a slightly under-damped transient response.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	You mentioned that you changed velocity from one level to another level. This was a steady state velocity and then you applied small deviations, small disturbances so that you could use the linearized model. Otherwise it would be nonlinear and you couldn't do linearization if you had steady state ramps, for example steep steady state ramps and velocity changes. You cannot describe the acceleration and deceleration period in the machine. Then the equations are nonlinear.
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	Yes, linearization of the nonlinear governing equations is valid for operation at only steady velocities. Our frequency response experiments were conducted by applying a small amplitude sinusoidal signal to a steady-velocity to extract the resonant frequency characteristics of the system. We have conducted extensive experiments and noticed that there is a good match between input frequency and the observed output frequency, which indicates that the system is mostly linear in our operating range.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	You applied this on the nonlinear equations. Did you provide any material damping in your investigations?
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	No. We consider the material to be linearly elastic, and we use a linear constitutive relation between tension and strain to obtain the span tension governing equation from strain equation. So, no material damping is assumed in the governing equation for tension.

Name & Affiliation	Question
Günther Brandenburg, Technische Universität München	If you simulate a system at steady state and this system is at standstill, it would be unstable because you get permanent oscillations and they are excited by some influence. The higher the transport velocity is increased, the better the damping becomes. If you work at very low transport frequencies, transport velocities, you may achieve very bad results because the theory shows large resonant peaks that never occur because the inner damping of the material, the web of paper or plastics. Is this your experience?
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	We have not been able to verify or experience the hypothesis that you mention. We have worked in a small speed range for our machine and at those speed ranges we did not observe the effect of damping as a function of web speed.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	What are the speed limits?
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	Our machine can run up to 500 feet per minute. We have conducted our experiments in the range of 100 to 200 feet per minute.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	The optimization of the control system which a gentleman wanted to know previously, did you apply linear theory to optimize the speed control and tension control? It is very simple to do when you have your linearized equations and did you neglect the higher frequencies because you have depicted an integrator and applied a PI controller to control the inner loop? How did you optimize this PI controller?
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	The inner speed loop PI controller is optimized for speed regulation with zero steady-state error due to step and ramp references and slightly under-damped transient response. The outer tension loop PI controller which provides a correction to the inner speed loop was designed based on the linearized equation for tension governing equation and was tuned experimentally to provide good tension regulation.
Name & Affiliation	**Question**
Tim Walker, TJWalker & Associates	What material did you use for the testing?
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	We used a polymer material called Tyvek which is 6 inches wide and 5 milli-inch thick, and has a modulus of about 94 kpsi.

Name & Affiliation	**Question**
Tim Walker, TJWalker & Associates	In Figures 11-13, you are showing the output for the dancer versus load cell number 2 control and load cell number 8 control, but the plots are created from which load cell? The dancer output is from load cell 8?
Name & Affiliation	**Answer**
P. Raul, Oklahoma State University	For those figures, the unwind roll control uses a speed-based tension control system where the inner loop is the speed regulator and the outer loop is the tension regulator. The feedback for the tension regulator is either dancer position or load cell measurement from one of the load cell roller Roller 2 or Roller 8. We have tried three scenarios: (1) the outer loop of the unwind roll control system is closed by dancer position feedback (Figure 11), (2) the outer loop is closed by tension feedback from load cells on Roller 2 (Figure 12), and (3) the outer loop is closed by tension feedback from load cells on Roller 8 (Figure 13). When we use dancer based feedback, we verify the performance of this strategy by measuring web tension on Roller 8.