THEORETICAL COMPARISON OF WINDING TENSION CONTROL METHODS

by

J. P. Ries
DuPont
USA

ABSTRACT

Several methods are used to control tension in the winding zone. The two most common methods use either a tension signal from a loadcell or a position signal from a dancer system. Both techniques control tension, however, the insertion of a dancer roll also affects the dynamics of the web transport line. The moving mass of the dancer roll and the fact that it can move add another degree of freedom to the system.

The method used in this analysis to compare the two control techniques was the closed loop transfer function. Differences between the two systems can be clearly seen in the frequency domain. Two excitations were considered. The first was an upstream disturbance from the in-feed roll velocity. The second was a torque disturbance on the winding spindle. The output variables of interest were the winding tension and the package velocity. Two identical zones were analyzed.

The closed loop transfer functions were obtained using an in-house, software program. Results showed that the loadcell system was better for low frequency disturbances because of the additional natural frequency created by the dancer roll. The dancer system provided better control in the mid-frequency range. Both systems were identical in the high frequency range because the dancer roll could not respond fast enough. The conclusion was that the successful use of a dancer system requires knowledge of the excitation frequencies and a good design for the dancer system.

NOMENCLATURE

A	web cross sectional area (in^2)
E	film elastic modulus (psi)
J_i	roll inertia (in-lb sec^2)
K_1	dancer feedback gain (in-lb/in)

K_2	loadcell feedback gain (in-lb/lb)
L_i	path length (in)
M	dancer mass (lb sec^2/in)
R_i	roll radii (in)
t	time (sec)
T_i	web tension (lb or psi)
x	dancer position (in)
τ	drive torque (in-lb)
θ_i	angular position (rad)
$\dot{\theta}_i$	angular velocity (rad/sec)

BACKGROUND

Good control of winding tension is required to form a quality package and avoid web-handling problems such as poor tracking and wrinkling. A winding zone is particularly vulnerable to large tension variations due to the changing angular velocity of the spindle and the noncircular shape of the package. Acceptable tension control requires that the system maintain the average tension near the set point and that any disturbances are attenuated and not amplified.

The two most common techniques to control winding tension are using a loadcell to feed back tension to the spindle drive or using a dancer position to provide the feedback signal. Ebler (Ref. 1) discussed the difference between the two techniques. Ries (Ref. 2) discussed the modeling of the winding zone and demonstrated the existence of multiple natural frequencies with the likelihood of resonance due to the changing frequency of the spindle. In Reference 3, he described an experimental technique to determine the lower natural frequencies of a winding zone during actual operation. The question often asked about a winding zone is "Which is better, dancer or loadcell control?" The goal of this study was to compare the two methods of control using identical winding zones and determine which method would theoretically provide the best control. The analysis uses the basic web span equations developed by Grenfell (Ref. 4) and incorporates the mechanics of mass and inertia similar to the system equations discussed by Reid and Lin (Ref.5)

DESCRIPTION OF THE MODEL

Since this was to be an analytical study, it was desirable to keep the physical model as simple as possible but still have it represent a typical winding zone. The in-feed would be a set of nip rolls whose velocity was fixed and not affected by tension. Three idlers would define the web path and the center winder would be under torque control with negligible drive system dynamics. The model is shown in Figure 1. Roll 3 is either a moving dancer roll or a stationary loadcell roll depending in the type of control being analyzed. For further simplification, only proportional control was considered in each case. Two excitations were applied; a variation in in-feed roll velocity and a variation in torque on the spindle/package shaft.

The mathematical representation for the rolls and the web spans are the same for the two models except in the case of roll 3 and the feedback representation. For the case of the loadcell system, the equation for roll 3 would be;

$$J_3 \ddot{\theta}_3 = R_3 [T_3 - T_2] \quad (1)$$

And the feedback equation would be;

$$\tau_m = - K_1 [T_3 + T_2] \quad (2)$$

The equations needed for the case of dancer control would be;

$$J_3 \ddot{\theta}_3 = R_3 [T_3 - T_2] \quad (3)$$

$$M \ddot{x} = [T_3 + T_2] - Mg \quad (4)$$

And,

$$\tau_m = - K_2 [x] \quad (5)$$

Combining equation (4) and (5) yields the control equation for dancer control.

$$\tau_m = - K_2 \iint \{[T_3 + T_2] /M - g \}dt \quad (6)$$

Thus, the feedback signal in dancer control becomes the double integration of the sum of the tensions on roll 3. This is often referred to as a Type 2 feedback. It is also why it is often referred to as tension control and not position control, although it does control the position of the dancer. It also controls the tension to the exact set value because the integration will not allow a constant error in $[T_3 + T_2] - Mg$. In this case, the set point for tension in steady state would be,

$$T_3 = T_2 = Mg/2 \quad (7)$$

Remember, in steady state the angular velocity of roll 3 would be constant and $T_2 = T_3$.

ANALYSIS OF PROBLEM

Because of the large number of equations, variables and parameters it was impossible to obtain a closed form solution and mathematically compare the two types of control. Therefore, an in-house program called TENDYN was used to simulate the solution. This program will provide either time domain or frequency domain solutions to web transport problems. The question of how to compare the two systems was also addressed. It was decided that the best way was in the frequency domain. This would show how each system would respond to a sinusoidal excitation arising in the web zone during normal operation. Thus, the system with the lower response amplitude would be better. The closed loop transfer function (ratio) between the important variable and the excitation or disturbance would be used for the comparison.

It was also found to be very difficult to use non-dimensional variables because of the many parameters. Thus, typical values for each parameter were assumed. The list below contains the values that were used for the eighteen parameters. The units are compatible with the TENDYN program.

$R_1 = 6$ in
$R_2 = 2.5$ in
$R_3 = 2.5$ in
$R_4 = 2.5$ in
$R_5 = 10$ in

$J_2 = 600$ lb-in^2
$J_3 = 600$ lb-in^2
$J_4 = 600$ lb-in^2
$J_5 = 60{,}000$ lb-in^2
$M = 120$ lbm.

$A = 0.06$ in^2
$L_1 = 24$ in
$L_2 = 5$ in
$L_3 = 5$ in
$L_4 = 96$ in

$E = 500{,}000$ psi
$K_1 = 100$ in-lb/in
$K_2 = 10$ in-lb/lb

The web represents a polyester film that is 60 inches wide and 0.001 inches thick. The rolls are typical sizes and the path lengths are representative of a compact winding zone. The winding package is near the end of its cycle with a 10-inch radius. The dancer feedback gain (K_1) was chosen such that a 1-inch deviation from the zero position would produce 100 in-lb of torque to change the speed of the spindle to bring the dancer back to set position. Likewise, the loadcell feedback gain (K_2) will produce 100 in-lb of torque when the tension deviates 10 lb from the set point, say 60 lb.

Two excitations were considered. The first was a variation in angular velocity of the in-feed roll, which is at the entrance of the zone. The second was a variation in torque on the spindle. This excitation could be from the drive motor or possibly the drive train of the spindle. In the case of the dancer roll system, the three variables of interest are the winding tension, spindle velocity and dancer velocity. For the loadcell system, the winding tension and spindle velocity were studied.

DISCUSSION OF RESULTS

The first difference between the two systems is the number of natural frequencies or eigenvalues. The loadcell system has four independent rolls (inertia) and therefore has four natural frequencies. The dancer control system has five natural frequencies because of the extra degree of freedom due to the dancer roll translation. Table I contains the natural frequencies for the parameters used in the study. The parameters are the same for both systems except for the feedback gains, which were selected to apply similar torque to the spindle as described in the section above.

Table I

Mode	Dancer System	Loadcell System
1	0.26 Hz	2.86 Hz
2	5.01 Hz	8.12 Hz
3	11.38 Hz	23.2 Hz
4	33.19 Hz	35.69 Hz
5	35.83 Hz	

The first difference between the two systems is the very low natural frequency in the case of dancer control. This is due to the position feedback and the double integration described by equation (6). Closing a feedback loop around a double, open loop pole creates a very low natural frequency. The three higher natural frequencies for the two systems were close in value because the dancer roll mass cannot move that fast. If the roll mass was very large, the three frequencies would be nearly the same. It must also be noted that changing the feedback gain will change the lower frequencies. The first natural frequency in the dancer system is very dependent on feedback gain.

Transfer Function Results

The transfer functions for the **dancer control system** are shown in Figures 2 through 7. Since natural frequencies mode 4 and 5 were so close in value, only four peaks appear in the plots. Figure 2, 3 and 4 show the transfer functions (TF) of the three key variables when the excitation was placed on the in-feed roll angular velocity. The results, when the excitation was a torque on the spindle, are shown in Figure 5, 6 and 7. The response functions for the **loadcell control system** are shown in Figures 8 through 11. The winding tension and spindle angular velocity are shown for the same excitation as before. The four peaks correspond to the natural frequencies. After the first peak is reached, the transfer functions all begin to roll off. In general, polyester film lines do not respond to excitations much **above 40 to 50 Hz**.

Comparison of Transfer Functions

Comparing the corresponding transfer functions for the two systems, one finds both similarities and differences. First, looking at Figure 2 and Figure 8 one can compare the ability of the two control systems to protect the winding tension from angular velocity variations from the in-feed roll. Both curves show the same rejection of very low frequency excitations at – 20db per decade. The amplitude ratios are the same in this region. The first difference is that the dancer system goes through a low natural frequency where the amplitude ratio rises to 10^3 at 0.26 Hz. Between 0.3 and 3 Hz, the loadcell system continues to rise but the dancer system response falls off. Above 5 Hz, both systems appear nearly the same. The effects of an excitation at the in-feed roll on the spindle angular velocity can be obtained by comparing Figure 3 and Figure 9. At low frequency, both curves approach an amplitude of 0.6, which is the ratio of the two radii. In other words, a low frequency oscillation at the pull roll will produce an equivalent amplitude oscillation at the spindle. For example, at zero frequency (dc), the spindle must run at the same velocity (fpm) as the in-feed roll. Near 0.26 Hz the dancer system amplifies the disturbance and the loadcell system amplifies the disturbance at 2.86 Hz. The response functions are similar above 10 Hz. Figures 4 and 7 show the dancer response amplitude ratios. In this feedback control scheme, the torque at the spindle is proportional to dancer position. Hence, the low frequency horizontal line in Figure 7 can be shifted with the feedback gain.

The second comparison was the effect of a torque excitation at the spindle on the system response. Figure 5 and 10 show how the torque excitation will affect the winding tension. Both curves have low frequency amplitude near 10^1, although the dancer system is slightly higher. A gain adjustment could offset this difference. The units on the amplitude are psi/in-lb, since tension is expressed as stress in TENDYN. The low natural frequency amplifies the curve in Figure 5, as usual. The curves roll off through the resonant peaks. Comparing Figures 6 and 11, the spindle angular velocity response is higher for the dancer system (Figure 6) in the low frequency range due to the natural frequency at 0.26 Hz. Both curves have a line drawn at an amplitude of 10^{-4} for reference. The scales are much different in the case.

CONCLUSIONS

Although quite different, both methods provide adequate control of winding tension. It was thought that this study would, through analysis, show that one method was superior to the other. Unfortunately, there are advantages and disadvantages to each one. Also, because of the differences in dynamic response functions, the better performing control system will depend on the frequencies of the disturbances.

The main difference between the two is that the dancer roll provides a signal that is the double integral of tension (if there is no spring attached). When used in a feedback loop, this relationship forces the error between the set point and the variable to be zero in steady state. Hence, the system will always try to keep the dancer at the set position and, thus, the tension at the set value. In this example, the set value would be one half the weight of the roll. The use of weights, air cylinders and pivoting rolls allows alternative ways to adjust the tension set point. For the loadcell system, there will always be a steady state error between tension and the set point when proportional control is used. This error can be reduced by increasing the proportional gain or eliminated by using proportional plus integral control. Regardless, there is no advantage to either system in the case of steady state error.

The main difference is in the dynamic response to periodic disturbances in the frequency domain. Examples would be eccentric rolls, motor speed variation, gearing errors or belt and pulley runouts. The **dancer system** has a very poor low frequency response due to the existence of a low natural frequency. This comes from the double pole at zero (double integration). Increasing the proportional gain will increase the frequency but also move the system more towards instability. This is the accumulation or "softness" effect that is often used to describe dancer roll control. For polyester film winders, the natural frequency typically lies between 0.5 and 2 Hz. For lower speed winding, the package often passes through this frequency and large variations in tension result. Thus, this system is better suited for high speed winding (above 500 fpm). On the other hand, in the mid-frequency range the dancer acts as a filter and these disturbances are attenuated. Higher speed winding will often fall in this range and have good results. In the high frequency range above 10 Hz both systems are the same.

The **loadcell system** has the better low frequency response and does not amplify disturbances in this range. It is well suited for low speed winding (below 500 fpm). The response functions do not have a mid- frequency drop (a zero or anti-resonance) like the dancer system. Disturbances in this range will be amplified by the first natural frequency. For winding zones with excitations in the mid-frequency range, loadcell control is not the right choice.

BIBLIOGRAPHIC REFERENCES

1. Ebler, N. A. et al, "Tension Control: Dancer Rolls or Load Cells," IEEE Transactions on Industry Applications, Vol. 29, No. 4, 1993.
2. Ries, J. P., "Longitudinal Dynamics of a Winding Zone," Proceedings of the Third International Conference on Web Handling, Oklahoma State University, Stillwater OK, 1995.
3. Ries, J. P., "Experimental Study of Winding Zone Dynamics," Proceedings of the Fourth International Conference on Web Handling, Oklahoma State University, Stillwater OK, June 1997.
4. Grenfell, K. P., "Tension Control on Paper-Making and Converting Machinery," IEEE Transactions, July 1964.
5. Reid, K. N. and Lin, K. C., "Control of Longitudinal Tension in Multi-Span Web Transport Systems During Startup." Proceedings of the Second International Conference on Web Handling, Oklahoma, State University, Stillwater, OK, June 1993.

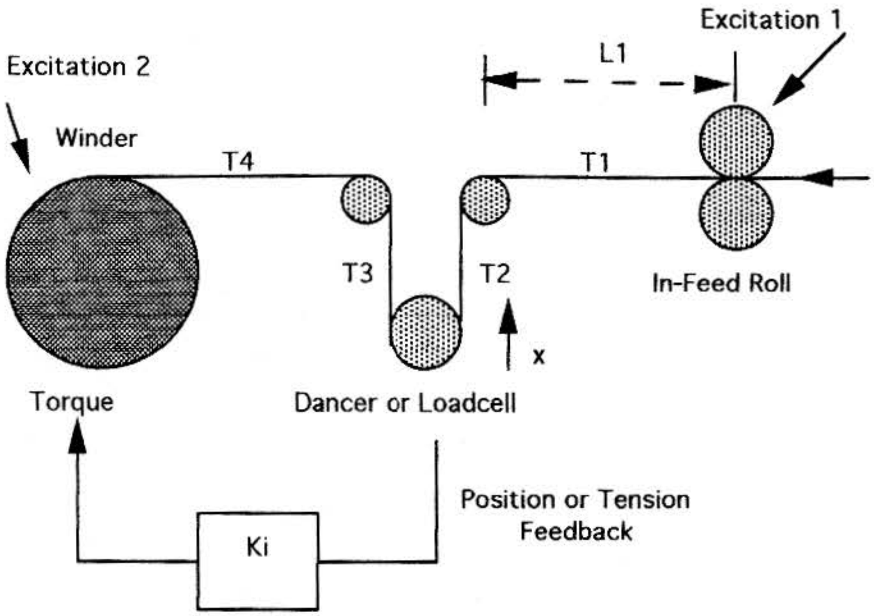

Figure 1. Schematic for the Winding Zone Model Used in the Study

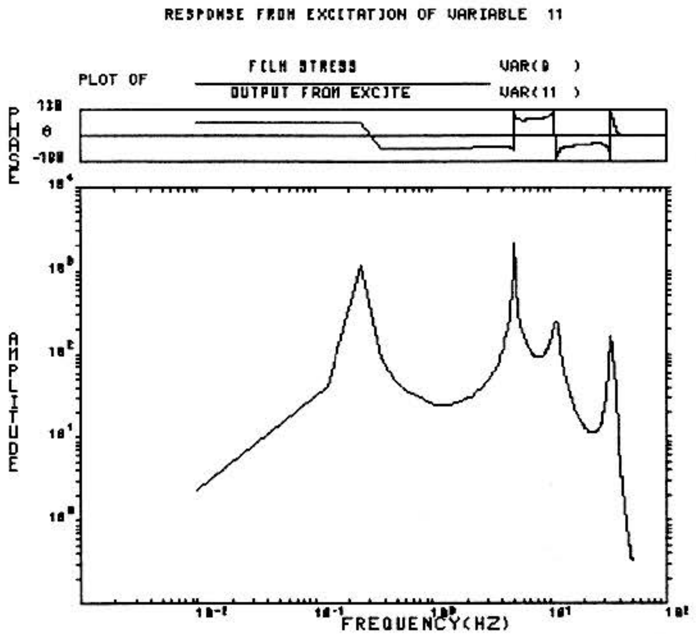

Figure 2. Response to Excitation from the In-Feed Roll with Dancer Control
TF = Winding Tension/ In-Feed Angular Velocity

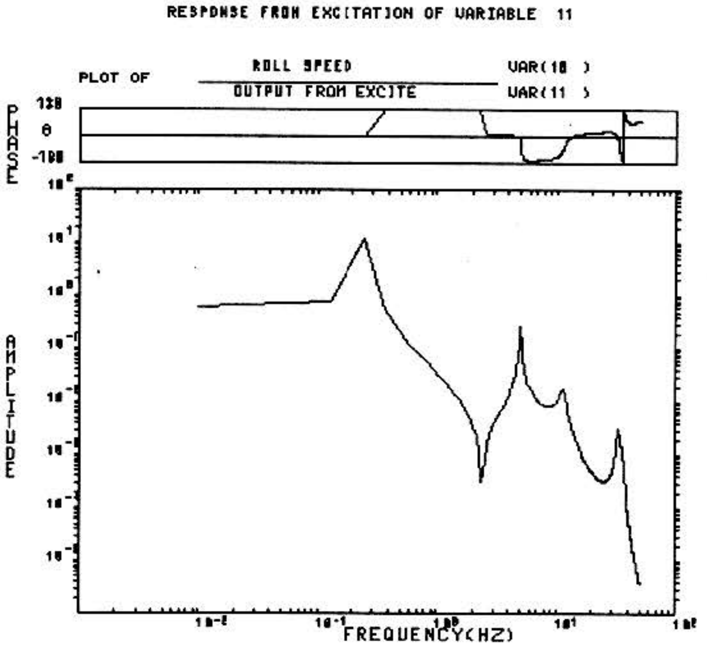

Figure 3. Response to Excitation from the In-Feed Roll with Dancer Control
TF = Spindle Angular Velocity/In-Feed Angular Velocity

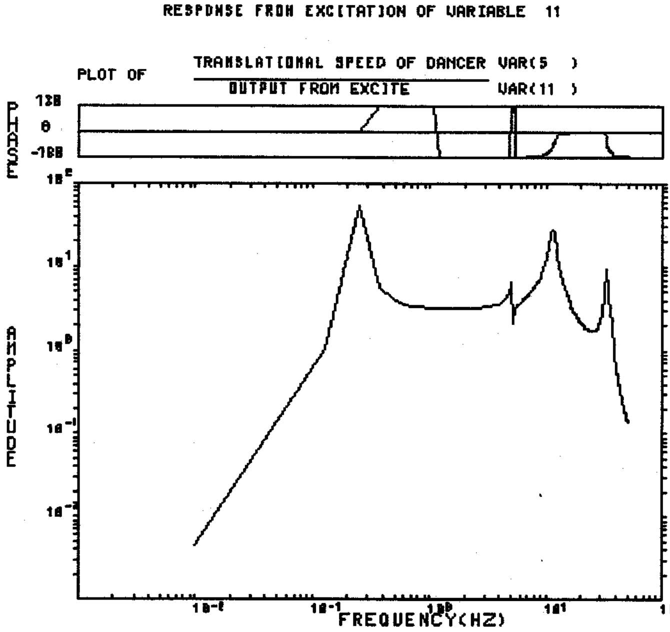

Figure 4. Response to Excitation at the In-Feed Roll with Dancer Control
TF = Dancer Velocity/ In-Feed Angular Velocity

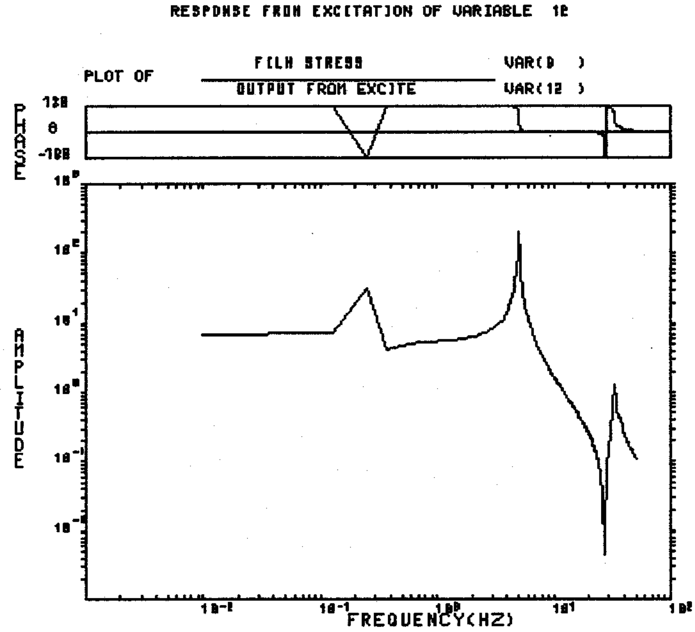

Figure 5. Response to Torque Excitation at the Spindle with Dancer Contr
TF = Winding Tension/Torque at the Spindle

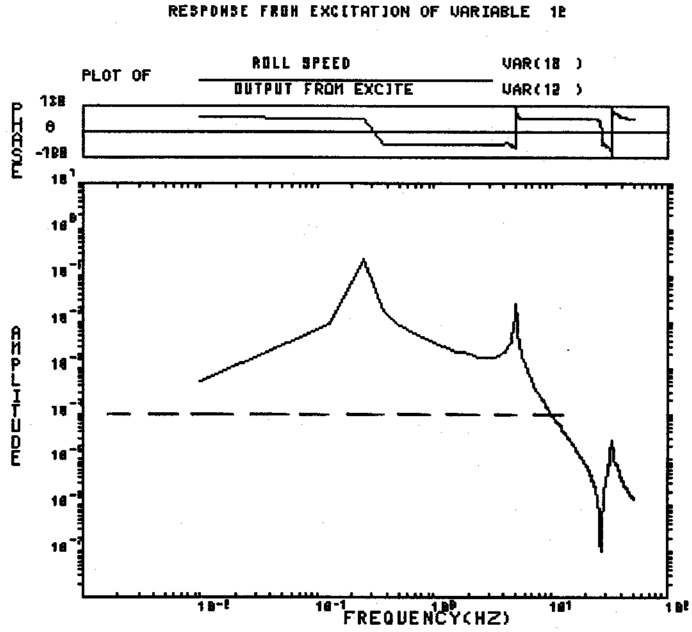

Figure 6. Response to Torque Excitation at the Spindle with Dancer Control TF = Spindle Angular Velocity/ Torque at the Spindle

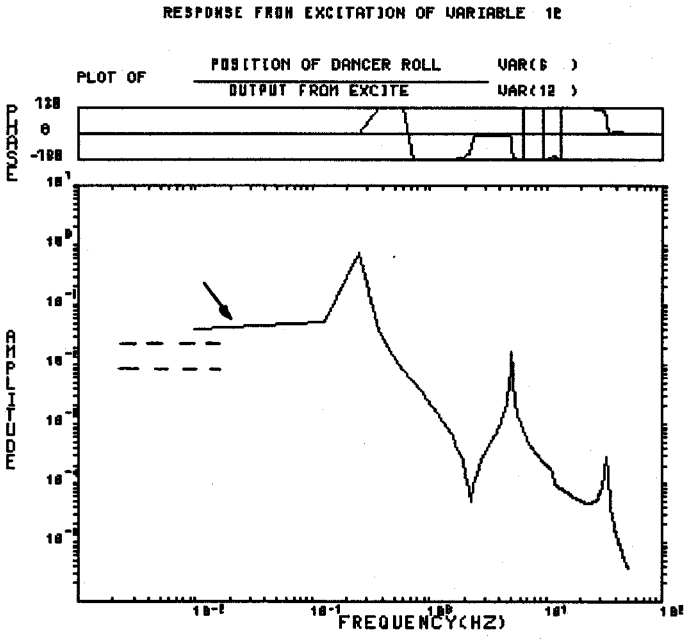

Figure 7. Response to Torque Excitation at the Spindle with Dancer Control TF = Dancer Displacement/ Torque at the Spindle

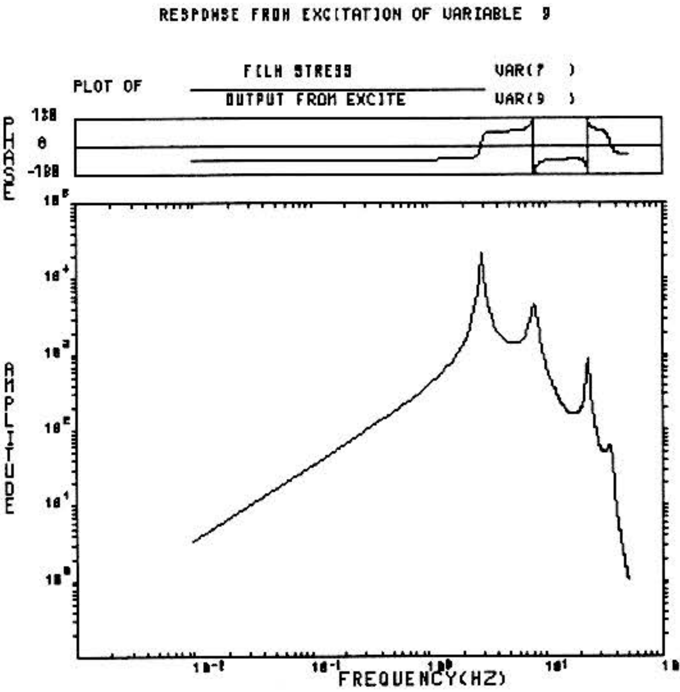

Figure 8. Response to Excitation from the In-Feed Roll with Loadcell Control
TF = Winding Tension/ In-Feed Angular Velocity

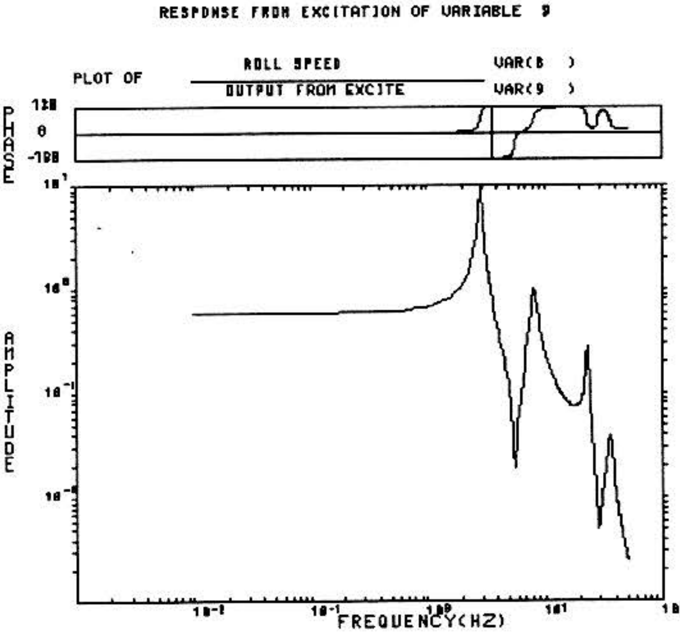

Figure 9. Response to Excitation from the In-Feed Roll with Loadcell Control
TF = Spindle Angular Velocity/ PR Angular Velocity

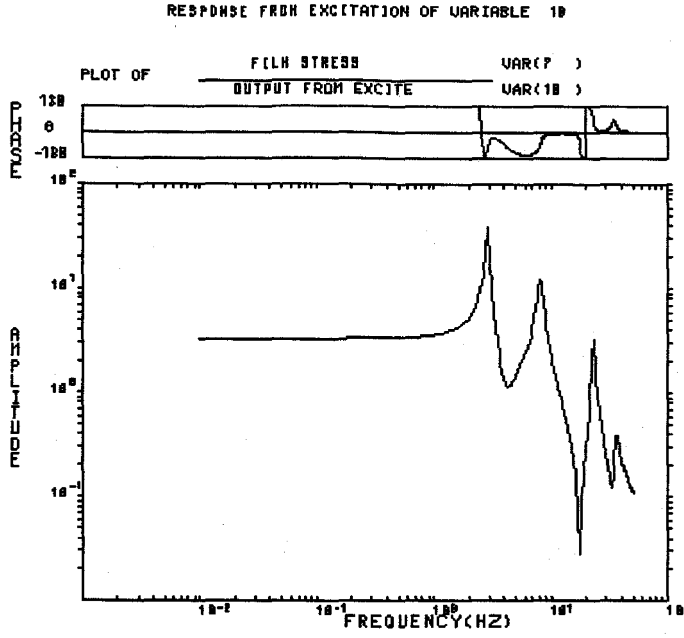

Figure 10. Response to Torque Excitation at the Spindle with Loadcell Control TF = Winding Tension/ Torque at the Spindle

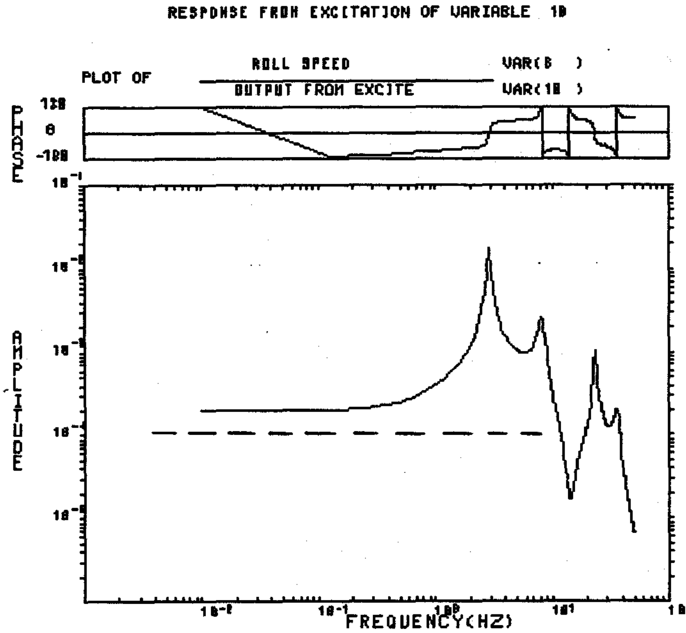

Figure 11. Response to Torque Excitation at the Spindle with Loadcell Control TF = Spindle Velocity/ Torque at the Spindle

J. P. Ries
Theoretical Comparison of Winding Tension Control Methods
6/7/99 Session 1 3:05 – 3:30 p.m.

Question – David Pfeiffer, JDP Innovations
Someone told me once that in a system like yours that you should first figure you have no springs on the dancer roll. If you put all the roll inertia at the outside of the surface of the roll and the weight of the rolls is sufficient to provide your tension force that its velocity insensitive. Thus no velocity disturbance will get through if you have all of the inertia on the outside shell of the roll. Now have you run into that? Or can anyone else comment on that?

Answer – J. P. Ries, Dupont
It will reduce the natural frequency, the second natural frequency. Are you asking if the inertia must rotate?

Question – David Pfeiffer, JDP Innovations
Yes. But does the rotating inertia cancel out the lack of tension when you suddenly decelerate and drop the roll? I've seen it and I have it instrumented it to measure it, but I've tested it in the lab and it seemed very good.

Answer – J. P. Ries, Dupont
We've seen that before. Some of the terms do drop out, but when a total system analysis is performed you still get transfer of disturbances across the dancer.

Question - Stephen Krebs, Web Technology
You were only talking about mechanical considerations, what about the electrical specifications? Did you look at different types of load cells, for example, would that change something in that picture you were drawing there?

Answer - J. P. Ries, Dupont
What type of load cells?

Question - Stephen Krebs, Web Technology
Yes, for example strain gage load cells versus LVDT load cells.

Answer - J. P. Ries, Dupont
No question, that does have an effect. John Shelton talked about that this morning.

Comment - Stephen Krebs, Web Technology
Yes, because with a dancer alone we have no reliable indication of web tension. We just do precision readings with the load cells.

Answer - J. P. Ries, Dupont
DuPont uses only strain gauge load cells. They have a frequency response flat to about 50 hz depending on the size of the roller. There is no sense in getting a transducer that will read a 1000 hz. tension variation when in fact your system won't support frequency content at a 1000 hz.. The two requirements of a good load cell tension sensing system are to (1) get the response frequency flat to some reasonable frequency and (2) to reduce

motion by using a high stiffness load cell, because low stiffness yields a sensor that is a bit of a dancer and a load cell. Thus I try not to use the kind of load cell that it infer tension by a deformation measurement because these cells typically have lower stiffness and compromise the frequency response of the tension measuring system.

Comment - John Shelton Oklahoma State University
To hopefully avoid any confusion between my paper and Jim's, mine is simpler. I study the limits of analysis and generalization. For example, the dancer with 2 rollers, when I analyze 3 rollers that were on stiff load cells I had a 7^{TH} order system. Jim not only has more complexity of the subsystem, but also the closed loop and so he has a more complicated system than I do.

Comment - J. P. Ries, Dupont
I don't have the patience you do, John.

Question - Jim Dobbs, 3M
When are you going to take those nice 50 hertz load cells and make some measurements of this?

Answer - J. P. Ries, Dupont
This is very typical of the kinds of measurements we make when we install the load cells. At the last IWEB conference I gave a paper on plotting the transfer functions. All it requires is to induce an excitation in feed on the velocity very, ever so slightly and then measure the tension. Do this at 0.5 hertz. Do an FFT and obtain the transfer function between the two, then sweep that frequency reading so that from .5 up to 30 hertz and plot the ratio and you get that function.

Question - Jim Dobbs, 3M
Okay, so these are experimental plots?

Answer - J. P. Ries, Dupont
No those are analytical.