WEB TENSION IN A FLOTATION DRYER

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ABSTRACT

In a flotation dryer, the web rides on a cushion of air and typically takes a "sine wave" path over the air bars. The non-straight path and the elastic effect of the air cushion interact with the normal tensioning of the web in the dryer zone. Equations were developed to describe the geometry of the web path, air pressure effect and the tensioning of the web in the zone. Computer simulation was used to solve the Equations simultaneously. It was found that the air cushion and pressure have no effect on the steady state tension. On the other hand, the dynamic response showed that the air cushion increased the time constant for the zone. Thus, the dryer zone appears to be much longer than the actual web length. Results also predict how riding height decreases as tension increases in time. Several cases were run at different air cushion pressures.

NOMENCLATURE

A	Cross sectional area of the web, $W \times t_f$
b	Air bar spacing
c	Air bar dimension (length)
E	Modulus of elasticity
h	Web path amplitude
ℓ	Arc length
L	Total length of web in the dryer
n	Number of air bars
p	Air bar cushion pressure
R	Air bar dimension (radius)
t	Time
t_f	Web thickness

T	Web tension in the dryer
T_0	Entering web tension
V	Average web velocity
V_1	Entering vacuum roll velocity
V_2	Exiting vacuum roll velocity
W	Web width
θ	Air bar dimension (angle)
τ	Time constant

BACKGROUND

Air flotation systems represent the latest technology for drying coated webs (Ref 1,2). As the web passes through the dryer, the solvent is removed from the coating by heat and mass transfer. A cushion of air is used to support the web and distribute heated air. Commercial dryers consist of an air distribution system, heating source, solvent removal and air bars. The key elements are the air bars which support the web on the cushion of air. The design of the bars must provide for optimum drying while maintaining the no-contact web condition. Figure 1 shows a typical configuration where the web takes a non-straight path through the dryer. This path is often referred to as the "sine wave".

The use of air flotation dryers create several web handling problems as discussed by Swanson (Ref 3) and others. This paper addresses the effects of a flotation dryer on longitudinal web tension control. As dryer tension is increased, the web stretches and the "sine-wave" begins to flatten. The analysis must include the actual length of web in the dryer and the mechanics of the air cushion which relates web tension to air cushion pressure and riding height. Because of these interactions, the presence of the air bars will greatly affect the dynamics of the zone. A dynamic model is needed to describe the behavior of a dryer zone and provide information for designing, tuning, and controlling the tension system.

ANALYSIS OF THE PROBLEM

Web Path Geometry

For easier understanding and analysis, a simple configuration will be assumed for the dryer zone. Figure 2 shows that it consists of an entering vacuum roll which grips the web and has controlled velocity V_1 and a similar exiting vacuum roll with velocity V_2. The straight line web path between the vacuum rolls is L_0. There are no idler rolls in the system. It is assumed that the straight web sections at the entrance and exit of the dryer are small compared to the overall length.

The geometry of one web path section is shown in Figure 3. Rather than a "sine wave", it is assumed that the path consists of a series of alternating circular arcs with radii R. The spacing between air bars is a fixed dimension (b). The other dimensions change as the riding height above the center line changes. From Figure 3, the following Equations can be written:

$$\ell = R\theta \tag{1}$$

$$\sin\left(\frac{\theta}{2}\right)=\frac{\left(\frac{b}{2}\right)}{R} \qquad (2)$$

$$\left(\frac{b}{2}\right)^2+(R-h)^2=R^2 \qquad (3)$$

The important parameters are the arc length of film (ℓ) for each air bar and the adjusted riding height (h). Neglecting the short sections at each end of the dryer and knowing the number of air bars (n), the total length of film in the dryer is simply,

$$L=n\ell \qquad (4)$$

Since the arc is assumed circular, the cushion pressure (p) and web tension are related by,

$$p=\frac{T}{R} \qquad (5)$$

The cushion pressure is <u>assumed constant</u> for changes in T and R. Equations (1), (2), (3), (4) and (5) can be combined into the following two equations for web length and adjusted riding height.

$$L=2n\left(\frac{T}{p}\right)\sin^{-1}\left(\frac{bp}{2T}\right) \qquad (6)$$

$$h=R-\left(R^2-\frac{b^2}{4}\right)^{1/2} \qquad (7)$$

<u>Web Dynamics Analysis</u>

The system configuration consists of the two vacuum rolls which control the web velocity entering and exiting the dryer and a long length of web which changes with tension as modeled in the previous section. The dynamic equation which describes the tension in the dryer zone is obtained by writing a mass balance for the web as it enters and leaves the zone. Grenfell, (Ref 4), Reid and Lin (Ref 5) and others have developed the basic equation in slightly different forms. When the web length varies and the stresses are small compared to the modulus (E), the equation can be linearized to the following form:

$$L\frac{dT}{dt}=\frac{EA}{W}(V_2-V_1)-VT+VT_0+\frac{EA}{W}\frac{dL}{dt} \qquad (8)$$

where tension T is expressed in force per unit width of web. The response of the system is represented by the simultaneous solution of Equations (5), (6), (7), and (8).

SOLUTION TO THE PROBLEM

Both the steady state solution and the dynamic response to a step change in vacuum roll velocity were studied. For large step changes in velocity the system is highly nonlinear due to the expression for web length in Equation (6). A dynamic simulation program with numerical integration software was used to generate the predicted responses. The first step was to examine the steady state solution.

Steady State Solution

Under steady state conditions, both web tension and web length are constant. Thus $\frac{dT}{dt} = \frac{dL}{dt} = 0$, and Equation (8) reduces to:

$$T = T_o + \frac{EA}{W}\left(\frac{V_2 - V_1}{V}\right) \tag{9}$$

A solution to the above Equation and Equation (6) yields the tension T and web length L. The increase in length due to the "wave" is quite small, normally less than 5%. Parameters E, A, W, V_2, V_1 and T_o would be known. Interestingly, Equation (9) is the same steady state Equation as a free span with velocities V_1 and V_2. Thus, the air cushion pressure and dryer parameters do not affect steady state tension. The tension in the dryer is determined by the incoming tension and the velocity difference between the two vacuum rolls. The dryer, as we will see in the next section, only affects the dynamic response.

Once the steady state tension, is known, the arc length and adjusted riding height can be determined as shown in Figures 4 and 5. Steady state conditions can be obtained in different ways. For example, in a typical dryer with an air bar spacing of 12.0", the riding height (h) might be 0.5". Thus the tension ratio T/pb is 3.0 from Figure 4. If the tension is controlled to 1.0 pli, then the cushion pressure would be,

$$p = 0.028 \text{ psi}$$

to support the web in the specified configuration. From Figure 5 (Equation 6) the arc length would be,

$$\ell = 12.0563 \text{ inches}$$

where the undeflected length is 12 inches.

Dynamic Solution

Any change in entering tension (T_o) or vacuum roll velocities (V_1, V_2) will cause a dynamic response and drive the system to a new steady state. Equations (5), (6), (7), and (8) were solved using a computer software program which utilizes block diagrams and integration routines. A case study was used to generate a set of solutions. Parameters were chosen to represent a typical web and dryer and the air cushion pressure was changed for each case. The input was a step change in the second vacuum roll velocity (V_2), thus causing an increase in web tension. The parameter values used in the study were:

(A) Fixed Parameters:

Parameter	Identification	Value
n	number of air bars	150
b	air bar spacing	12 inches
V	average web velocity	100 in/sec
V_1	inlet velocity	100 in/sec
E	web modulus	500,000 psi
W	web width	60 inches
t_f	web thickness	0.002 inches
T_o	incoming tension	0.5 pli

(B) Adjustable parameter: air cushion pressure (p)

$0.005 < p < 0.06$ psi

(C) Input variable: exit vacuum roll velocity (V_2)

Step change from 100 to 100.1 in/sec at $t = 0$.

The results are shown in Figure 6 for several different values of air cushion pressure. For low pressures, the curves look like a simple "first order system" response to a step input. For zero air pressure, the zone path length is 1800 inches. At V=100 in/sec, the time constant would be,

$$\tau = \frac{L}{V} = 18 \text{ seconds}$$

The effect of the air cushion (dryer) is to lengthen the time constant and add nonlinearity to the system. Note that regardless of pressure, all cases approach the new steady state condition of $T = 1.5$ pli for $V_2 = 100.1$ in/sec. This is the steady state value predicted by Equation (9). The longer time constant is not due to the extra length in the dryer. This is a small effect (4% at $p = 0.05$ psi). The dynamic changes in adjusted riding height for the same cases are shown in Figure 7. Since the steady state height depends on both tension and pressure, it decreases to a new steady state when V_2 is changed to 100.1 in/sec.

CONCLUSION

The effect of an air flotation dryer on the dynamic response of web tension was analyzed. A step change in velocity was studied to illustrate the nonlinear response. There were two significant results that came out of this analysis. First, the steady state tension was shown to be independent of air pressure and web path. Like a simple free span, it depends only on incoming tension, vacuum roll velocity difference and the web parameters.

The second result was that the system responds like a "lag" type system where air cushion pressure lengthens the time it takes to reach steady state. For large changes, the system is highly nonlinear. However, if the changes in tension are small, the system can be linearized and an effective dryer length (L_e) can be computed using,

$$\frac{dL}{dt} = \frac{\partial L}{\partial T}\frac{dT}{dt}$$

and then from Equation (8)

$$L_e = L - \frac{EA}{W}\left(\frac{\partial L}{\partial T}\right)_{\text{steady state}}$$

Then the dryer model becomes a simple free span model with length equal to L_e which will be greater than the actual dryer length, L because $\frac{\partial L}{\partial T} < 0$.

BIBLIOGRAPHIC REFERENCES

1. Fraser, W. A. R. "Air Flotation Systems" Theoretical Considerations and Practical Applications", Paper. Film and Foil Converter" May, June 1983.

2. Cohen, E. D, Lutoff, E. B., Modern Coating and Drying Technology, VCH Publishers, Inc., New York, 1992.

3. Swanson, R. P. "Air Support conveyance of Uniform and Non-Uniform Webs", Proceedings of the Section International Conference on Web Handling, Web Handling Research Center, Oklahoma State University, Vol II, 1993.

4.. Grenfell, K. P "Tension Control on Paper-Making and Converting Machinery", IEEE Transactions, July, 1964.

5. Reid, K. N., Lin, K. C. "Dynamic Behavior of Dancer Subsystems in Web Transport Systems", Proceedings of the Second International Conference on Web Handling, Web Handling Research Center, Oklahoma State University, Vol II, 1993.

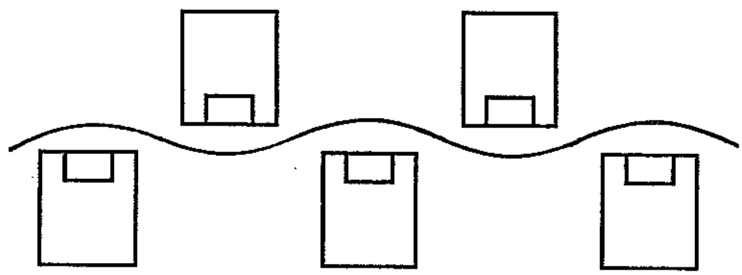

Figure 1. Web Path Over the Air Cushion Nozzles

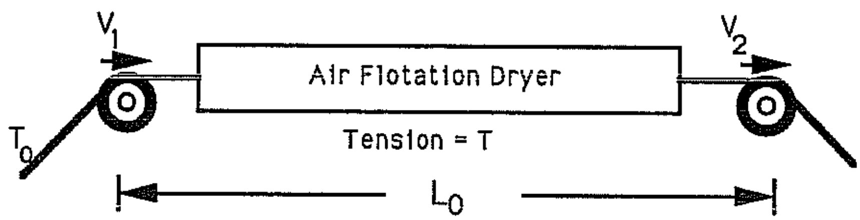

Figure 2. Configuration and Dryer Zone Parameters

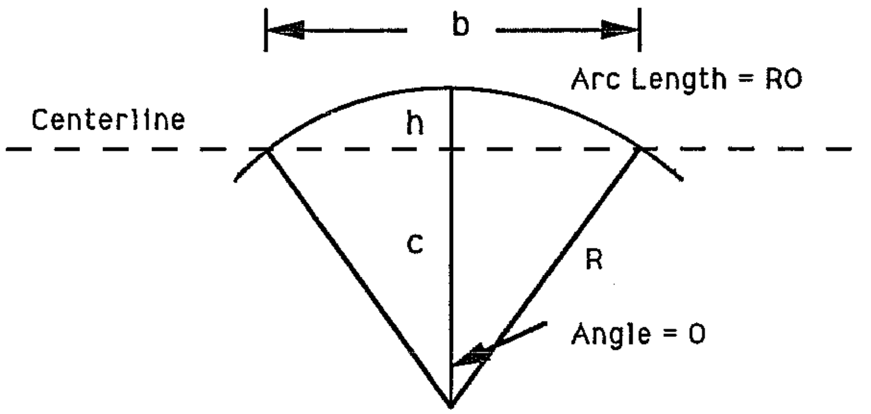

Figure 3. Geometry of the Web Path

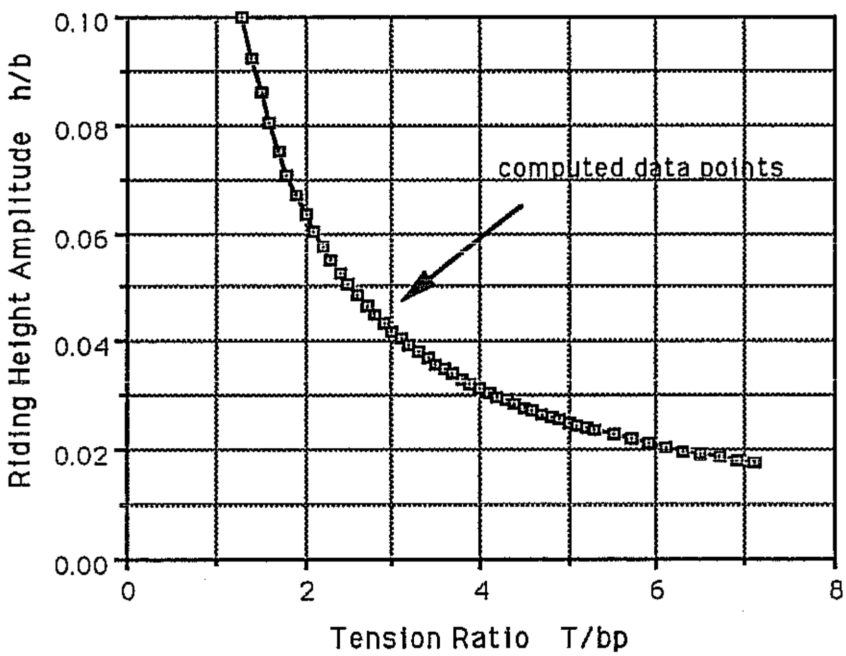

Figure 4. Steady State Riding Height
Amplitude vs Tension

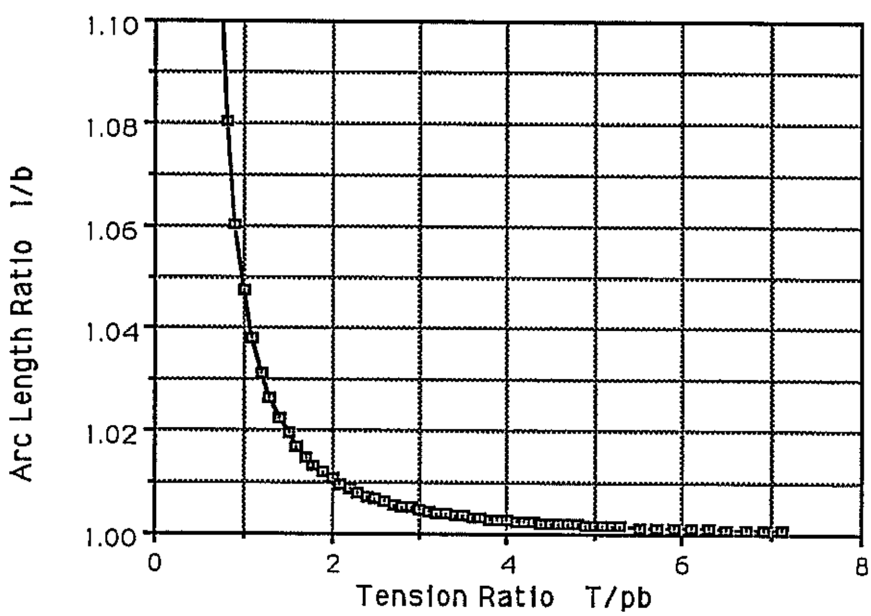

Figure 5. Web Path Arc Length at Different Tensions

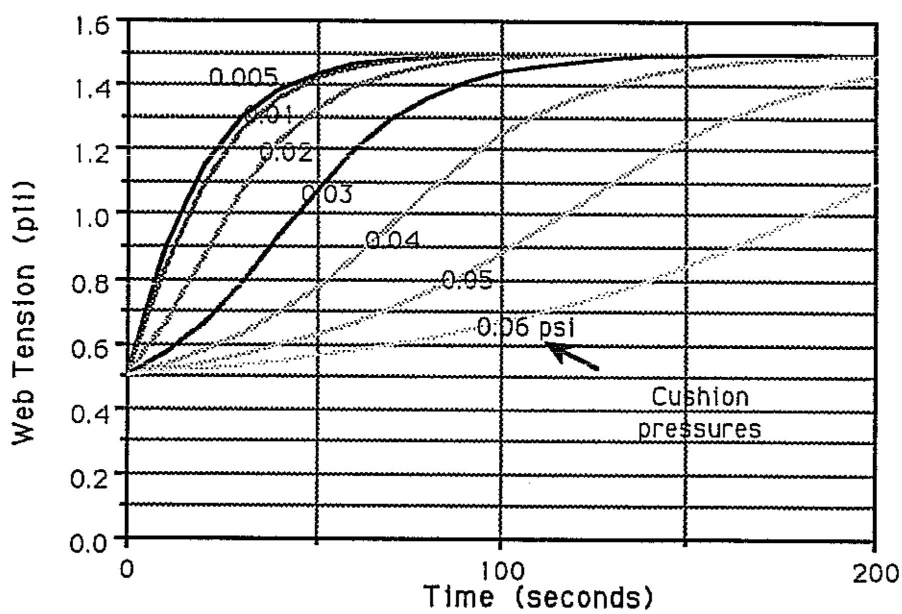

Figure 6. Dynamic Response of Web Tension for Several Air Cushion Pressures

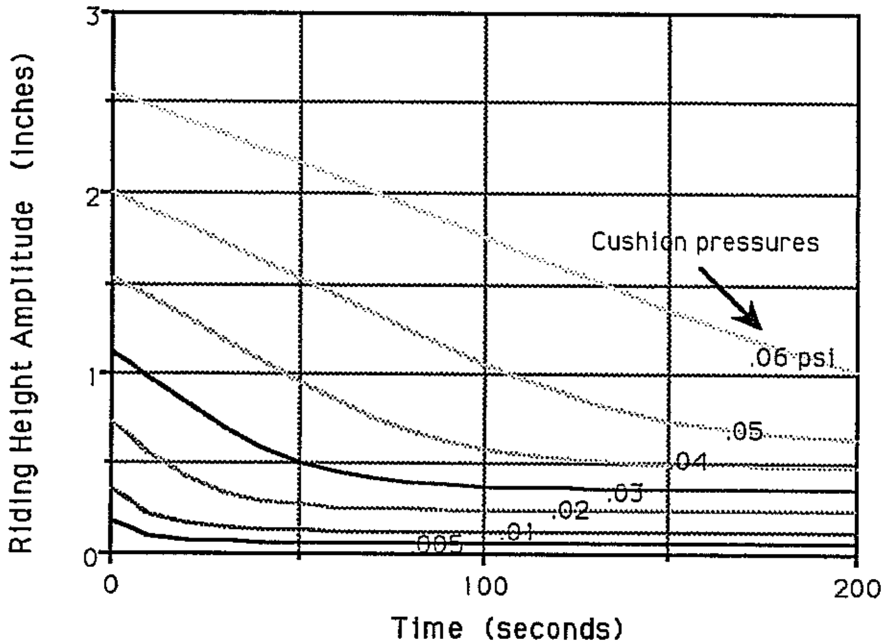

Figure 7. Dynamic Response for Riding Height Amplitude for Several Air Cushion Pressures