COUPLING BETWEEN OUT-OF-PLANE DISPLACEMENT AND LATERAL STABILITY OF WEBS IN AIR-SUPPORT OVENS

by

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ABSTRACT

In drying ovens where the web zig-zags over and under air-support bars, the web sometimes drifts to one side or the other until it runs into the oven wall. This divergence is shown to be coupled to out-of-plane displacements in the form of lateral tilting of the web where it curves over the air-support bars. Limiting these out-of-plane displacements is necessary in order to prevent excessive lateral divergence and the resulting damage to the web and its coating. Air-bar characteristics which control out-of-plane displacements are identified.

INTRODUCTION

In many web handling applications, substantial lengths of moving web are supported by air bars. For example, when polymeric films are coated or papers are printed, they may be dried in flotation ovens. Persistent problems in these situations are lateral instability and wrinkling. Coupled out-of-plane and lateral motions are key factors in these phenomena. The relationship between out-of-plane deflection and lateral divergence can be analyzed by three different approaches:

1. the reduction in lateral beam stiffness due to the zig-zag geometry;
2. the geometrical coupling between lateral tilting of a zig-zagging web and the lateral deflection of the web; and
3. the lateral aerodynamic forces on a tilted web.

From these analyses a model for the lateral divergence of a web in a flotation oven can be constructed. Experiments which provide the coefficients needed in such a model are reported, and air-support-bar configurations which improve lateral control can be identified.

EXTENSIONAL STIFFNESS

Our first approach to analysis notes that the lateral control of webs is directly proportional to the stiffness of the web as a beam in lateral bending, EI. E is Young's modulus of elasticity, an extensional property of the web material. I is the sectional second moment which relates extensional and beam-bending characteristics: $I=bh^3/12$, b being the thickness and h the width of the web, if we are looking at *lateral* (cross-machine) bending.

In real situations, equivalent extensional moduli can arise not only from material properties, but also from geometrical conditions. We can investigate this by looking at ordinary extension of a web. For example, a vertical web has only the material-dependent extensional spring constant

$$k_{mat} = \frac{Ebh}{L} \tag{1}$$

where L is the length of the web; but a horizontal web hangs in a catenary curve and, even if its material were inextensible, would have an apparent spring constant

$$k_{cat} \cong \frac{12T^3}{L^3}\left(\frac{g_c}{\rho bhg}\right)^2 \cong \frac{3}{128}\left(\frac{L}{z_{sag}}\right)^3\left(\frac{\rho bhg}{g_c}\right) \tag{2}$$

This approximation is valid as long as the sag z_{sag} is much smaller than the span length L. The spring constant k_{cat} is a non-linear function of the tension T, but can be used as a constant for small variations about the equilibrium tension.

If both material properties and the geometry are taken into consideration, then the effective spring constant is

$$\frac{1}{k_{eff}} = \frac{1}{k_{mat}} + \frac{1}{k_{cat}} \tag{3}$$

Then, the "apparent Young's modulus" can be taken as

$$E_{app} = \frac{k_{eff}L}{bh} \tag{4}$$

Using this value from linear extension allows us to introduce the effect of sag into our analysis of the lateral beam stiffness of sagging webs. In other words, the extensional stiffness can be related to bending stiffness by $(EI)_{eff} = k_{eff}h^2$. Moreover, from Equation (3) it is evident that if either k_{mat} or k_{cat} is much smaller than the other, then the larger one may be neglected. When there is a great deal of sag, the web will be very "loose" laterally, even if the material's E is very high.

Following a suggestion by Dr. J. J. Shelton, we can use this same approach to analyze the flexibility of the web due to its zig-zagging between lower and upper air support bars. We have air-jet induced forces which support the web alternately from the top and from the bottom. If the angle α in Figure 1 is moderate, we can say that the support force

$$F_{bar} = 2T\sin\alpha \tag{5}$$

If the tension T changes, then either the support force F_{bar} or the angle α or both must change. The angle α depends on the spacing L of the air-support bars and the maximum deflection z_{max} from the mean path:

$$\alpha = \arctan\left(\frac{2z_{\max}}{L}\right) \cong \left(\frac{2z_{\max}}{L}\right) \tag{6}$$

This z_{max} results from the positioning of the air bar plus the air cushion supporting the web; ordinarily, the variations in the air film are much smaller than the spacing L, so that the angle α changes very little. On the other hand, the support force F_{bar} varies with the air film thickness. We can treat the air cushion as a support spring with its own apparent spring constant, the slope of the force versus film thickness curve:

$$\kappa \doteq \frac{dF_{bar}}{dz_{\max}} \tag{7}$$

which can be measured for various designs of air-support bars. Solving for the relationship between tension T and deflection z_{max} for small perturbations about the equilibrium,

$$\frac{dT}{dz_{\max}} = \frac{\kappa L}{4z_{\max}} - \frac{F_{bar}L}{4z_{\max}^2} \tag{8}$$

where the first term describes air-bar fluid mechanics, and the second term support-oven geometry. From these expressions we can calculate an apparent spring constant k_{zig} similar to those obtained for straight and catenary webs. From our data, it appears that the first term will dominate for all but the flattest web paths, since $\kappa >> F_{bar}/z_{max}$ in most cases. Therefore, our first approximation is

$$k_{zig} \cong \frac{\kappa}{8}\left(\frac{L}{z_{\max}}\right)^2 \tag{9}$$

The complete expression for the spring constant of each span, as started in equation (3), becomes

$$\frac{1}{k_{eff}} = \frac{1}{k_{mat}} + \frac{1}{k_{cat}} + \frac{1}{k_{zig}} \tag{10}$$

but the last term will normally dominate in practical situations, so that $k_{eff} \cong k_{zig}$., and $(EI)_{eff} \equiv k_{zig}h^2$.

We see that the effective Young's modulus is strongly reduced in air-support ovens and that the degree of reduction is obtainable from the measurements of κ-values.

Applying these results, we find a reduction in lateral stiffness which can be interpreted as a loss of lateral control. We may visualize this as an "accordion-like" or "bellows-like" flexibility effect. Equation (8) shows that there are two strategies for retaining as much control as possible: either maximize the coefficient κ through careful selection of air-support bar design, or else minimize the angle $\alpha \equiv 2z_{max}/L$ in the oven lay-out.

GEOMETRICAL COUPLING

In a second method of analysis, we note that out-of-plane deflection and lateral divergence at a support bar can be related by looking at the steering geometry of a web sliding over a turning bar with a modest wrap angle, θ in the notation of Figure 2 (or twice the value of α in Figure 1). Unlike a turning roller with surface friction, which steers by seeking a normal approach angle for the web, a turning bar does not control the lateral position of the web, but lets it slide towards the "low" side of the bar. On the other hand, it does control the angle β through which a web deflects laterally (as seen looking down on the web). If one side of the bar is lifted slightly in the plane of the bisector of θ, so that it tilts at an angle ϕ (as seen by a viewer looking in the machine direction), the deflection is a function of wrap angle and tilt angle. If all angles are small,

$$\beta \cong \theta\phi \cong 2\alpha \cdot \phi \qquad (11)$$

where all angles are in radians. Although our air bars do not tilt, a slight difference in the air film between web and air-support bar is equivalent to a tilting bar, and has the same effect.

Therefore, slight perturbations in the air gap will tilt the web at its wrap over the bar (as seen looking in machine direction) and lead to a lateral "bend" (as seen from above). To minimize this effect, we can use two strategies: either control the air gap closely by maximizing κ so that strong forces oppose side-to-side variation of the air gap, or else minimize the wrap angle provided by the oven geometry. This is the same conclusion we came to in the previous section.

By adjusting the web's tilt at the bar intentionally, we can direct the web laterally, either as a set-up adjustment or as part of a control loop. The adjustment can be made mechanically by actually tilting the bar, or aerodynamically by adjusting air flows differentially between the two sides of the web. It must be remembered, however, that turning-bar control has different characteristics than friction-roller control. Turning-bar tilt is weaker in effect than roller tilt; depends on the tilt angle in the plane of the bisector of the entering and departing webs rather than the tilt angle in the plane of the entering web; and has less propensity for causing wrinkles.

There is also the possibility of passive control: an arrangement of the slots in the air bar which tends to induce a compensating tilt when there is an error in lateral position. In the air bars near the entrance of the oven, this could be achieved by having more air flow near the edges of the web than in the center. There are historical instances where the opposite effect was inadvertently achieved by using air bars which gave insufficiently wide air support.

LATERAL FORCES

The third method of analysis observes that tilt introduces lateral forces on the web: the air pressure on a tilted web pushes it to the side. Our investigation of lateral stability identifies inadvertent lateral forces on the web due to inadvertent perturbations of web tilt.

The first-order analysis assumes that the normal forces due to pressure on the web are much larger than any drag forces. Any tilt of the web results in a lateral component of force throughout the length of the wrap (Figure 3). Therefore either the tilt or the wrap angle must be minimized to achieve stability, as we concluded in the analyses of the previous two sections. Conversely, active or passive control of tilt through air-flow balance can be used to govern lateral direction.

More thorough analysis needs to add drag-force effects due to lateral air flows. These flows go from high-pressure to low-pressure regions, or from the narrower air gap (if κ is positive) to the wider air gap. That means that they will tend to be opposite to the first-order effects discussed so far.

AIR-BAR SUPPORT CHARACTERISTICS

The three analyses presented above all confirm the relationship between the "stiffness" of air-bar support and the lateral stability of webs in air-support ovens. We would generally expect these ovens to show some steady drift of the web to one side or the other (a "static" or divergent rather than "dynamic" or oscillatory instability). Our analysis shows that proper selection of air-bar characteristics can minimize the tendency to drift.

Preliminary screening of a simplified single-jet air bar and five commercial air-support bar designs was carried out, using a rigid flat plate with numerous static-pressure taps instead of a web. Pressure distributions for each type of air bar were obtained. Figure 4 (Pinnamaraju 1992) shows a typical result for an "air pad" type bar for different air cushion thicknesses h_0. This pressure profile can be integrated to give total support force at each air cushion thickness, Figure 5 (Pinnamaraju 1992). The support force varies with the spacing h_0 between the air bar and the plate. Generally, a negative slope indicates a positive κ for positive stability—the support force decreases as the web lifts off—but the positive slope observed with one of the air bars suggests the possibility of instability. Very thin air cushions, and very steep negative (stable) slopes were obtained with the last air bar tested, an asymmetrical "air foil" design, which has a very different pressure distribution, Figure 6 (Nisankararao 1994). These results explain why air-foil bars have sometimes proven useful for reducing lateral divergence in air support ovens.

Lateral tilting was investigated in more detail by obtaining lateral pressure distributions at various tilt angles, as shown in Figure 7 (Nisankararao 1994). The pressures at each location are somewhat lower than would be expected at that local gap from untilted-web data. This indicates that there are significant transverse air flows, and that strip theory is not exact in this confined situation. The basic trends presented from the preliminary, untilted measurements still hold, but transverse drag forces may not be entirely negligible, and may reduce the divergence predicted from early results.

The pressure measurements in air were augmented by flow visualization in water (Perdue 1993). Observations indicate that the diverging flow at the sides of the air bars can lead to local oscillatory instabilities. These may be related to the "buzzing" observed under some operation conditions. The perforated trailing flaps installed on some air-foil type bars would tend to damp this phenomenon.

FUTURE WORK

The sensitivity of the measurements not only to air gap, but also to machine-direction tilt of the web (as seen in the cross-machine direction) suggests that the flexibility of the web is a significant additional factor. This is particularly true for air-foil type bars, for which the measured pressure distributions are very non-uniform (refer to Figure 6). Analysis of hovercraft stability (Chang and Moretti 1994) indicates that web speed may also be a factor in flow stability.

SUMMARY

The connection between out-of-plane perturbations and lateral stability has been demonstrated in three different ways: equivalent beam stiffness, geometrical coupling, and induced lateral forces. The importance of flotation force as a function of air gap has been shown: a rapid reduction of support force with increasing air gap increases lateral stability. Pressure measurements on rigid webs have been used to demonstrate the effect of air-bar design on the lateral stability of webs in flotation ovens.

ACKNOWLEDGMENTS

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CITED WORKS

Chang, Y.-B., and Moretti, P. M. (1994) "Ground-Effect Theory and Its Application to Air Flotation Devices," Third International Conference on Web Handling, June 18-21, Stillwater, Okla.

Nisankararao, S. K. V. (1994) "An Experimental Study of Aerodynamic Forces of Air Bars," M. S. thesis, Oklahoma State University. (Also published as a WHRC report.)

Perdue, D. (1993) "Lateral Stability Investigation of Air Bar and Web Interaction for Use in Flotation Ovens," M. S. thesis, Oklahoma State University. (Also published as a WHRC report.)

Pinnamaraju, R. (1992) "Measurements on Air Bar/Web Interaction for the Determination of Lateral Stability of a Web in Flotation Ovens," M. S. report, Oklahoma State University. (Also published as a WHRC report.)

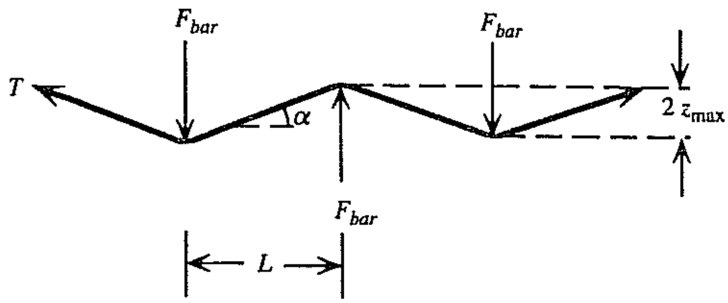

Figure 1 Forces on the web

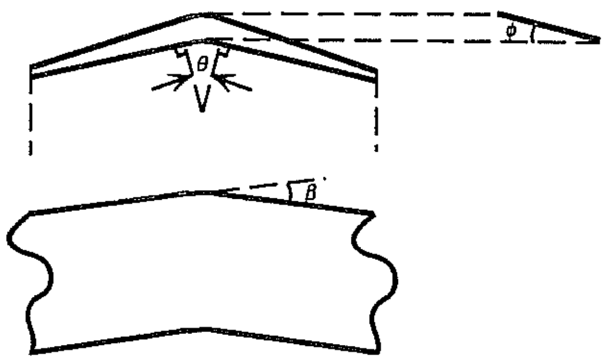

Figure 2 CMD, MD, and top views of web

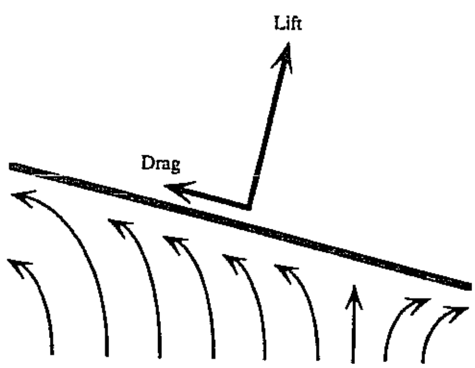

Figure 3 Aerodynamic forces on web

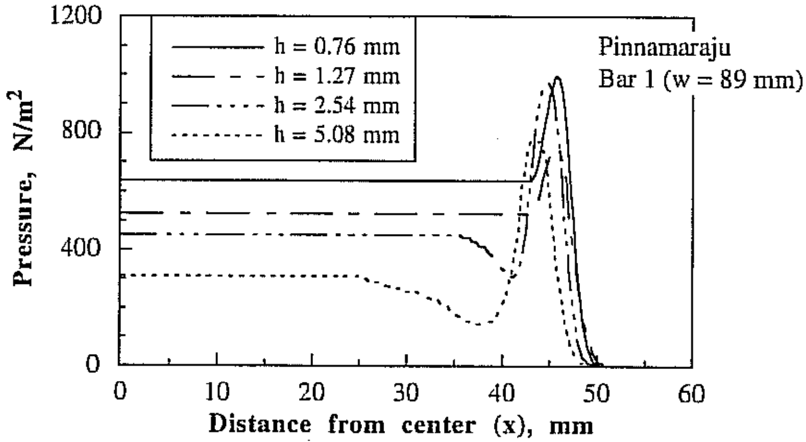

Figure 4 Effect of flotation height on the pressure distribution (Pinnamaraju 1992)

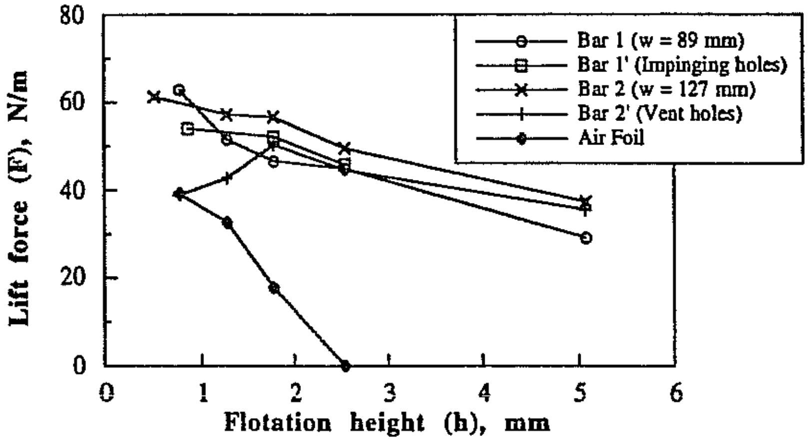

Figure 5 Effect of flotation height on the lift force (Pinnamaraju 1992)

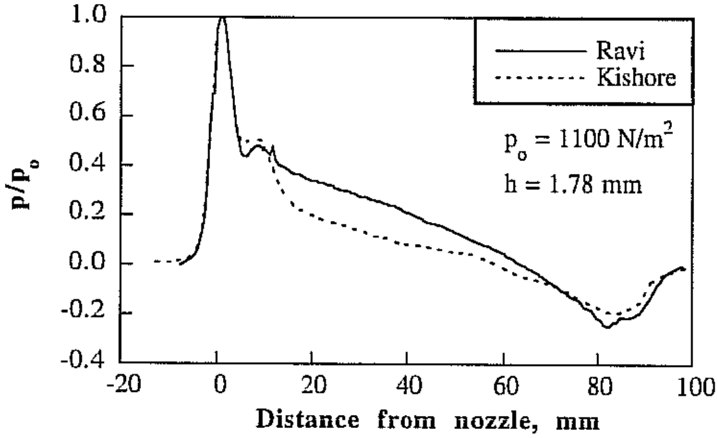

Figure 6 Pressure distribution for air foil bar (Nisankararao 1994)

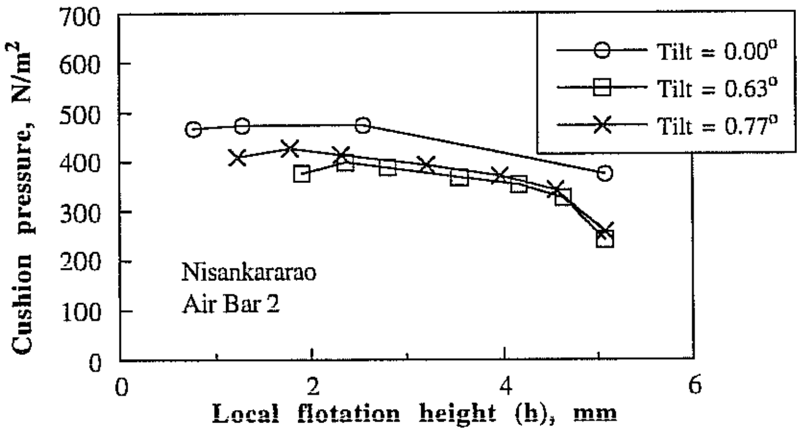

Figure 7 Effect of CMD tilt on the local pressure (Nisankararao 1994)

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Question - Do you feel that with high-speed webs the results would be different?

Answer - How serious is it that we neglected the velocity of the web? I think web velocity does make a difference, especially on air foil bars. However, you have to remember that the air velocity coming out of the slots tend to be quite a bit faster than the velocity of the web. Therefore our stationary-web test caught the main effects. I think its important to go on to second-order effects such as the web transport, and we will do that next.

Question - How about the changing characteristics of the web inside the dryer from the entrance to the end, or from wet to dry?

Answer - Since we are not looking at longitudinal effects, longitudinal property changes should not matter. We are interested in lateral steering, similar to what you get in a web sliding over a bar or a stopped roller. Unlike a rotating roller, which seeks a normal entrance angle, a tilted bar or stopped roller lets the web slide to the low side. An air bar can appear tilted, because of different air-pad heights from one side of the machine across to the other, so you get inadvertent steering because of inadequate control of the tilt of the web. A logically extension of this work would be intentional steering control. We would tilt these bars aerodynamically or mechanically in order to get lateral steering. When you have to deal with cambered webs and want to come out centered at the end, this would be one possible strategies. So far, however, the only thing we've investigated is how to minimize lateral divergence; active control will come later.

Question - What is the relative magnitude of the effective spring constants due to material properties, sag, and zig-zagging? In the paper I gave at IWEB-2, I did some crude calculations showing that aerodynamics forces are relatively small.

Answer - I think the zig-zagging is usually dominant. Catenary sag is important only if there is a long span. You are correct that aerodynamic drag forces are less important than the normal pressure or lift forces generated by the jets in the air bars. We will look at drag forces when we get to second-order effects.

Question - What kind of web speeds are typically through these dryers? You said the jet velocity were typically high relatively to the web speeds?

Answer - Some coating machines with flotation ovens run at less than 300 ft per minute. That's not at very high speed. In general the air speed will be several times the web speed.

Thank you.