Cross-machine variation of paper curl on a twin-wire machine

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ABSTRACT *Paper machine trials were performed to study across-the-reel variation of paper curl for a commercial twin-wire machine. The headbox jet speed was varied, with all other machine variables kept as constant as possible. Full-width sheet samples were collected and examined for curl on a xerographic copier grade of paper. A good correlation was obtained between curl and the reciprocal of the specific CD modulus of elasticity, indicating that the same processes that affect the development of elasticity also affect curl. Cross-machine variation of curl is attributed, in part, to a variation of restraint in the cross-machine direction.*

KEYWORDS
Curl
Deformation
Dimensional stability
Drying
Elasticity
Moisture content

A sheet of paper will curl, or experience a departure from flat form, as a response to changes that bring about in-plane differences in web dimension through the thickness of the sheet. The basic causes of curl are nonuniform expansions and contractions of the fibers resulting from moisture variations. Paper will also exhibit changes in dimension in response to temperature changes. However, in most practical situations, the hygroexpansive behavior will almost always dominate (*1*).

Differences in dimensional change across the sheet thickness can result from exposure of the two faces to different moisture conditions. Alternatively, curl can result from differences in structure or composition through the sheet when both faces are exposed to similar moisture conditions.

Background

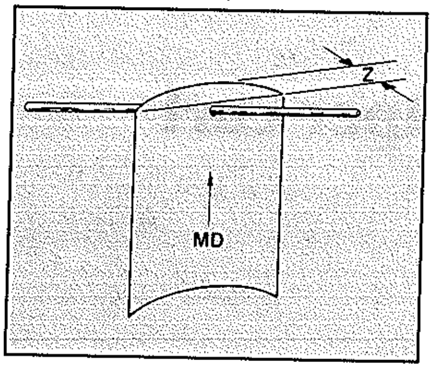
The first recorded mathematical description of curl can be attributed to Smith (*2*), who, based on simple geometry, developed an expression for the radius of curvature of a multi-ply paperboard sheet as a function of sheet thickness and percentage contraction of the liner. From measurements on strips cut in both the machine direction (MD) and cross-machine directions (CD), Smith found good agreement between measured liner shrinkage and that shrinkage predicted using his model and measurements of curl.

Spitz and Blickensderfer (*3*) treated paper as a thin two-ply laminated beam and developed an expression for curl in terms of change in relative humidity, ply thicknesses, ply contractivities (expansivity), and ply moduli of elasticity. With some simplifying assumptions, they showed that the change in sheet curvature is proportional to the product of the change in relative humidity and the difference in expansivity of the two plies and that it is inversely proportional to sheet caliper.

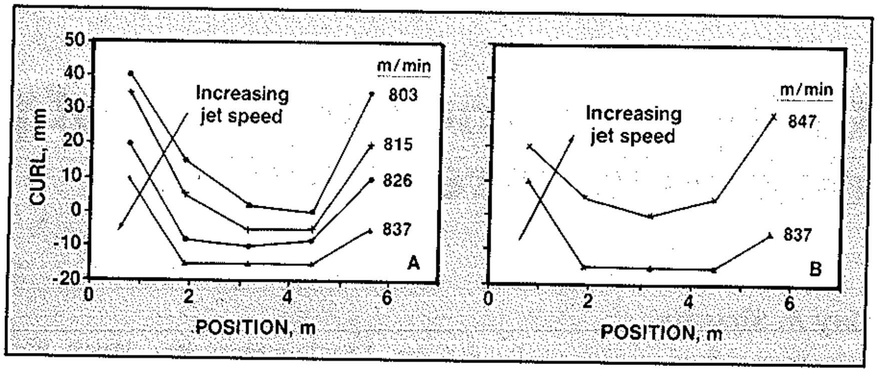
Carlsson (*4*) derived a general expression for sheet curvature based on lamination theory for a multi-ply structure consisting of an arbitrary number of plies, where the orientation of the plies can be varied. Carlsson, Fellers, and Htun (*5*) simplified this general expression for plies that are similarly oriented where the effect of Poisson's ratio is neglected. Their expression for sheet curvature is similar to that developed by Spitz and Blickensderfer for a two-ply structure.

Carlsson also presented results for sheets where the layers were formed separately and couched together. A general good agreement of experiment with theory was found, with some deviations being observed at higher humidities. Pijselman and Poustis (*6*) have used Carlsson's equations to evaluate the effect of variations of elastic moduli, ply thicknesses, and hygroexpansivity coefficients on curl for a three-ply

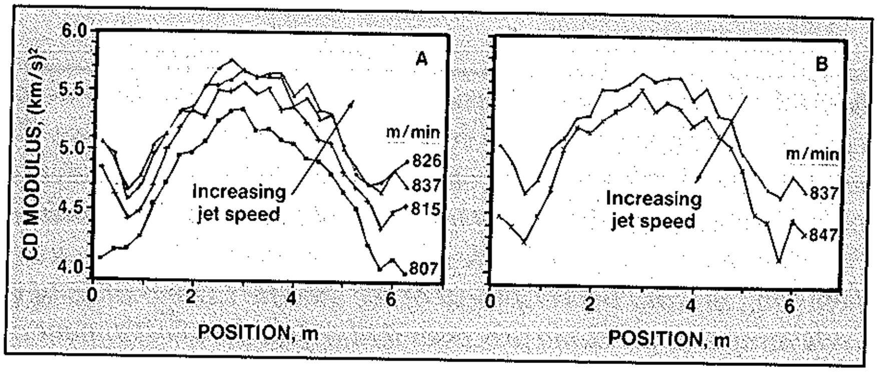
1. Curl measurement, where the distance Z is the recorded value



2. Cross-machine curl profiles, with a wire speed of 814 m/min



3. Cross-machine profiles of CD specific modulus of elasticity



structure. They concluded, in agreement with Carlsson, Fellers, and Htun, that the major prerequisite for obtaining a flat product is to maintain symmetry through the sheet with respect to hygroexpansivity.

Factors that influence sheet hygroexpansivity include beating, fiber orientation, pressing, and drying restraint. A discussion of these factors may be found in the related *Proceedings* paper (*7*).

For paper made on fourdrinier machines, Glynn, Jones, and Gallay (*8*) concluded that the fundamental basis for curl lies in the differences of fiber orientation through the sheet. They showed that on the wire side of a sheet, more fibers tend to be oriented in the machine direction than for the top side of the sheet. For similar drying conditions, curl curvature was found to correlate with a measure of the differences in fiber orientation from the top to the wire sides of paper made on two separate machines.

Both Hendry and Newman (*9*) and Green (*10*) reported measurements on differences in fiber distribution and curl behavior with respect to relative humidity changes that confirm Glynn's observations. Guest (*11*) reports that curl is dependent on jet-to-wire speed ratio with curl being considerably reduced for ratios approaching unity. LeBel and Stradal (*12*) have found that the MD:CD tensile ratio as varied by jet-to-wire adjustment is one parameter that can be used for curl control. Refining energy, fiber length index, and dryer steam pressure ratio were also reported as influencing curl.

For sheets made on a centrifugal dynamic former, Koran, Bussieres, and Prud'homme (*13*) report a correlation of curl with average fiber orientation, pointing out that this factor is more important than the variation in orientation through the sheet thickness. Rutland (*1*) has also observed this effect for sheets made on the same type of former.

Structural two-sidedness in terms of fines and density differences have also been found to influence curl. Hendry and Newman (*9*) reported that laboratory sheets tended to curl away from the sides of higher fines contents at high humidities and toward those sides for exposure to low humidities. For both commercial papers and dynamic former sheets, Rutland (*1*) indicates that curl tendency correlates well with differences in density through the sheet.

The effects of nonuniform drying have also been documented (*14, 15*). The use of differential steam pressures between the top and bottom cylinders in the last dryer section is a tool that papermakers have traditionally used for curl control.

To date, studies of curl have involved either fourdrinier-made paper or handsheets. To our knowledge, no studies regarding twin-wire machine paper have been published. Furthermore, little is published on CD variations of curl. Here, we report on the causes of CD curl variation for a twin-wire machine. The paper from this machine has exhibited a greater tendency to curl at the edges than at the center of the reel.

Mathematical description of curl

Considering a paper sheet as a two-ply structure with equal ply thicknesses, Carlsson, Fellers, and Htun (*5*) developed an expression for sheet curvature, K, as follows:

$$K = 24\,(\beta_2 H_2 - \beta_1 H_1)/[t\,(E_1/E_2) + (E_2/E_1) + 14] \qquad (1)$$

where

β = coefficient of hygroexpansion

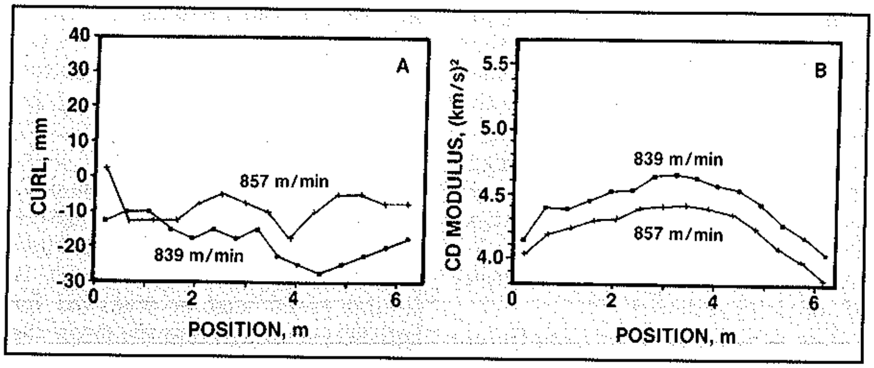
H = change in equilibrium moisture content

t = sheet thickness

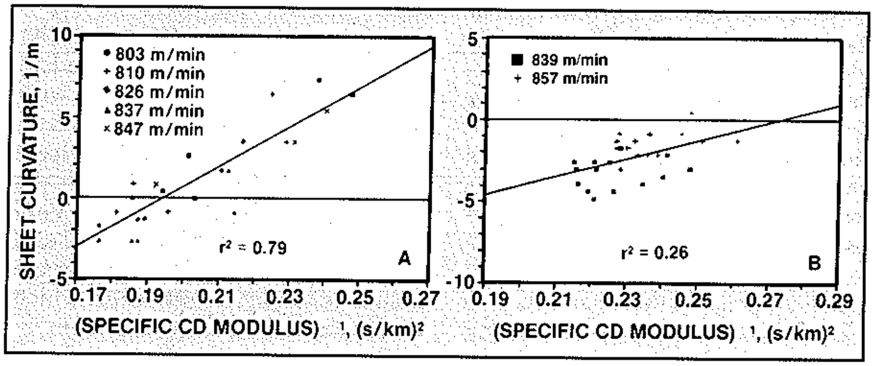
E = Young's modulus of elasticity.

The subscripts 1 and 2 refer to the two sides of the sheet. A positive curvature denotes a sheet concave to

4. Cross-machine profiles for curl (A) and for CD specific modulus of elasticity (B), with the wire speed at 832 m/min



5. Sheet curvature vs. the reciprocal of the specific CD modulus of elasticity for (A) data from Fig. 2 and (B) data from Fig. 4



the Side 1.

The expression for sheet curvature can be simplified further with the following assumptions. First, the quantity in the brackets in the denominator of Eq. 1 is not sensitive to changes in modulus ratio. For paper not being intentionally laminated, this quantity can be taken to equal 16 without any significant loss of accuracy. Equation 1 can be reduced further if it is assumed that both sides of the sheet will experience equal changes from the equilibrium moisture conditions:

$$K = [1.5\,(\beta_2 - \beta_1)H]/t \qquad (2)$$

The quantity K/H may be viewed as the change in sheet curvature per unit change in equilibrium moisture content. This quantity has been referred to as the "curling tendency." Thus, for a given sheet thickness, curling tendency will be directly dependent only on the difference in hygroexpansivity between the two sides. As a result, we may expect that any CD variations of curling tendency will be associated with CD variations of the difference in hygroexpansivity between the two sides of the sheet.

Paper machine trials

Machine parameters

The machine configuration consisted of: a twin-wire former; a three-nip press section, the first nip being double felted and the following two being single felted (with felts facing the No. 1 side); and four dryer sections, with three prior to a size press and one after it. The No. 1 side refers to the top side of the sheet as it comes from the last dryer cylinder and approaches the reel, while the bottom side is Side 2.

Results are reported for trials conducted on two separate occasions. The trials consisted of varying headbox jet speed while maintaining all other machine variables as constant as possible. For both trials, a 75-g/m^2 xerographic copier paper was being produced. Wire speeds and headbox freenesses were recorded at 814 m/min (2670 ft/min) and 832 m/min (2730 ft/min) and 450 mL and 495 mL CSF, respectively. Reel moistures were under 5%.

The furnish to the paper machine consisted of 100% bleached softwood kraft pulp. The sheet was filled to the 10% level and was internally sized using rosin and alum addition.

Testing

Curl measurements were conducted at the mill. Immediately after turnup, samples were taken at the reel, were cut into 8.5 × 11-in. sheets with holes punched near the top of each sheet, and were hung in an enclosed chamber at a controlled relative humidity of 30%. As shown in **Fig. 1**, MD curl was recorded as the maximum perpendicular distance from the chord that intersects the top two edges of the sheet to the sheet itself. A template was used to determine these distances.

Elastic properties of the samples were determined acoustically using a SST-250 sonic sheet tester manufactured by Nomura Shoji Co., Tokyo, Japan. Specific moduli of elasticity were determined according to the relation

$$S.E.M. = E/\rho \cong c^2 \qquad (3)$$

where

ρ = sheet density

c = the measured sonic wave speed.

Because the Poisson ratios were neglected in this equation, the moduli are overestimated by about 5-10% (*16*).

Results

In **Figs. 2A** and **2B**, measurements of curl are presented for samples taken at five CD locations for five different jet speeds. The data are plotted on two separate graphs for purposes of clarity. The recorded jet speeds refer to jet speed at the point where the jet makes first contact with the wire. Actual jet speeds in the forming zone were lower as a result of changes in pressure and elevation.

At the lowest speed (803 m/min), the curl at each point across the reel is toward Side 1, with more curl occurring at the edges than at the center of the reel. As jet speed is increased to 815 m/min, the curl is reduced at the edges and starts to curl toward the No. 2 side at the center of the reel. With further increases in speed to 826 m/min and 837 m/min, the profiles continue their shift towards the No. 2 side. For the next speed increase to 847 m/min, the trend reverses itself, with the curl profile shifting back towards the No. 1 side.

In **Figs. 3A** and **3B**, measurements of specific CD elastic modulus are shown for the same runs. Measurements of specific MD elastic modulus, the geometric mean of the MD and CD moduli, and sonic orientation angles are reported elsewhere (*7*).

Samples were split with a Beloit Sheet Splitter, and sonic orientation angles were determined for each side. Typically, no consistent orientation differences between the two sides were observed. Fines and ash contents were also determined for the split samples. Higher percentages of fiber fines and ash were observed on the No. 1 side. However, both fiber fines and ash contents tended to remain constant across the reel.

On the same machine several months later, a similar trial was conducted with two different jet speeds and with the wire speed being held constant. Drying was held constant during the trial, but the steam pressure differential between the top and bottom cylinders in the dryer section was different from that during the previous trial. Previously, the top cylinders were run hotter than the bottom cylinders, while for this trial the bottom cylinders were hotter.

Results from this trial are plotted in **Figs. 4A** and **4B**, where cross-machine profiles of curl and specific CD elastic moduli are shown, respectively. Lower elasticities with less CD variation were found than previously. The curl values were all toward the No. 2 side, with less CD variation occurring. Changes in jet speed again affected both the CD moduli and curl values.

Discussion

For for the first trial (Fig. 3), the run at 837 m/min produced the sheet with the largest CD elastic moduli. At the lower and higher speeds, lower values occurred. The changes in CD elasticity resulting from changes in jet speed were much less than the overall changes across the reel. In Fig. 2, a somewhat similar trend may be observed for the curl values. The greatest curl toward the No. 2 side occurred for the run at 837 m/min. At the lower and higher speeds, lesser values occurred (either less toward the No. 2 side or more toward the No. 1 side). As for the CD elasticities, the general, across-the-reel curl changes tended to be larger than curl changes resulting from changes in jet speed. These initial observations suggest that a correlation might exist between the modulus of elasticity and curl.

Both de Ruvo *et al.* (*17*) and Green (*18*) report that hygroexpansivity is inversely related to the modulus of elasticity. However, Salmén *et al.* (*19*) point out that the elastic modulus is influenced by drying restraint in the interval between 30% and 60% solids content, whereas the hygroexpansivity is influenced more by drying restraints imposed during the final stage of the drying process when the sheet is at solids contents above 80%. They illustrate that hygroexpansive behavior can be changed by the drying strategy without change to the elasticity.

Here, for the purpose of examining the curl behavior, it is assumed that the coefficient of hygroexpansion may be expressed over range of elasticities encountered in the experiment as:

$$\beta_i = (A_i/E_i)+B_i \qquad (4)$$

In this equation, A_i and B_i are some unspecified functions of the furnish and of the papermaking processes. In this empirical model, while hygroexpansivity increases with decreased elasticity, changes in hygroexpansivity may also occur without change to elasticity.

Substituting Eq. 3 into Eq. 2 then yields an expression for the changes in sheet curvature, K, for a moisture change, H, as follows:

$$K = (1.5H/t) + [(C+1)(CA_2 - A_1)/2C]/[E + (B_2 - B_1)] \qquad (5)$$

where

C = the ratio E_1/E_2

E = the arithmetic mean = $(E_1 + E_2)/2$.

Thus, this equation predicts that sheet forming parameters that affect elasticity may also affect curl. The extent to which elasticity changes will influence curl will be dependent on the magnitude of the term in brackets in Eq. 5 that multiplies the reciprocal of the modulus.

In **Figs. 5A** and **5B**, sheet curvature (measured at 30% RH) is plotted as a function of the reciprocal of the CD modulus of elasticity for the data shown in Figs. 2 and 4. A good correlation may be seen for the data from the first trial (r^2 = 0.79) with a less distinct correlation being found for the second trial (r^2 = 0.26). A similar trend may be observed for both sets of data in that the lower the elasticity, the less the curl becomes toward the No. 2 side, or the more it tended toward the No. 1 side.

These results are interpreted as supporting the prediction of Eq. 5 that processes which affect elasticity can also affect curl and curl tendency. This conclusion also agrees with the observations of Guest (*11*) and LeBel and Stradal (*12*), who have found that curl is dependent on the jet-to-wire difference. That curl would vary with elasticity would also imply that a correlation with average fiber orientation might occur, which in fact has been observed (*1, 13*).

With regard to the CD variation of curl, the results presented here suggest that variations in restraint in the cross-machine direction can lead to curl variation across the reel. CD elastic modulus tends to decrease from the center to the edge of the reel, which indicates a decrease in restraint and hence, an increase in shrinkage in the cross-machine direction as the edges are approached. With increasing shrinkage, the hygroexpansivity of each side of the sheet will increase. With large hygroexpansivities, the differences in hygroexpansivity should also increase, leading to increasing curling tendencies as the edges are approached.

Considerably more curl variation occurred across the reel for the first trial than for the second. Furthermore, for the first trial, the CD elastic moduli were larger. At first, one might assume that with larger moduli, the web would exhibit less hygroexpansivity. However, the larger changes in elasticity across the reel indicate that more shrinkage was probably occurring, which would indicate higher hygroexpansivities. Higher hygroexpansivities could account for the greater variation across the reel and the tendency to curl.

From these observations and the work of others (*20, 21*), if shrinkage is allowed to occur, then the degree of dimensional instability will vary across the web. Furthermore, the magnitude of the dimensional instability will likely be sensitive to the pulp type and refining characteristics. If a sheet could be more completely restrained, the web should achieve a more uniform dimensional stability across its width with the overall dimensional stability becoming less sensitive to variations in pulp type and the degree of refining.

Summary

The history of a twin-wire machine indicated that the paper exhibited a greater tendency to curl at the edges than at the center of the web. Paper machine trials were performed in which jet speed was varied, with all other machine variables kept as constant as possible. Regardless of jet speed or the position on the reel where the samples were taken, a good correlation was found between curl and the reciprocal of the specific CD modulus of elasticity.

These results indicate that the same processes that are affecting the development of elasticity are also affecting curl. CD variation of curl is attributed, in part, to a variation of restraint in the cross-machine direction.

Papermakers have long recognized the need for more uniform CD restraint. The use of expander rolls (*22, 23*), increasing dryer felt tensions, and the use of stenters (*24, 25*) have had varying degrees of success. Because of recent innovative developments in dryer technology (*26*), the future holds promise for the ability to achieve more uniform CD restraint, and hence, production of paper with more uniform dimensional stability.

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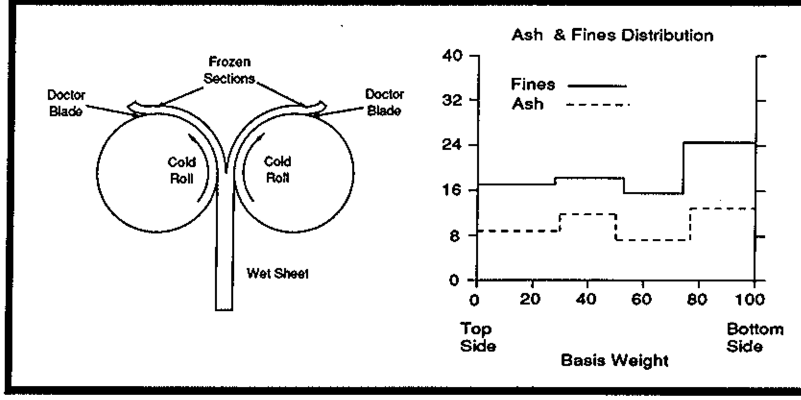

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