Estimating paper machine CD shrinkage profiles from headbox actuator data

S.J. I’Anson and W. W. Sampson
Paper Physics Research Group
Department of Paper Science, UMIST
PO Box 88, Manchester, M60 1QD, UK.

Abstract
The profile of cross-machine direction (CD) shrinkage on a paper machine is typically measured off-line using image-analysis techniques to determine the profile of the dimensional change caused in the marks of one or more forming fabrics. Here we show present theory that allows an estimate of the CD shrinkage profile to be obtained from the settings of actuators used at the headbox to give CD grammage control. The data required to determine the shrinkage profile is already recorded as part of standard process monitoring and control procedures. Application of the technique is demonstrated using data from the literature.

Introduction
A number of authors [1-4] have demonstrated that the profile of cross-machine direction (CD) shrinkage on a paper machine can be determined from measurements of periodic marks in the sheet caused by one or more forming fabrics; the profile of the dimensional change in the sheet manifesting itself in the profile of the marks. Shrinkage in the dryer section is known to influence the dimensional stability of the sheet and hence print register and runnability in printing processes. Coupled with the fact that papermakers seek to maximise the width of the sheet at reel-up, knowledge of the shrinkage profile, the way that it changes over time and how it is affected by changes of raw materials or machine conditions is undoubtedly of value.

Currently, the vast majority of CD shrinkage profiles are measured in specialist laboratories, with a time-lag of, at best, a few days. Although it is possible to install equipment on paper machines to capture images of the moving web and process these to measure shrinkage profile [5] this is unusual, probably because of a combination of cost and the complexity of the task.

During forming, low consistency stock is projected in a jet from the slice of the headbox and impinges onto one or more forming fabrics. Actuators that deflect the flexible slice lip, or dilution of the stock via actuator controlled valves across the headbox manifold, are used to control the delivery of stock across the width of the slice. The amount of deflection or the amount of dilution is determined by a feedback loop from the basis weight sensor to automatically control grammage profile. As CD shrinkage of paper is greater at the edges of the machine than at the middle, the slice gap is always bigger, or the dilution lower, in the middle of the headbox. It has been shown recently that this profile can be fitted by a similar function to that used to characterise shrinkage profiles [6].

There is substantial literature concerning the control of CD variability in paper properties and identifying the mapping of paper properties measured on-line at reel-up to the corresponding location in the headbox. Chen [7] used Kalman filtering to separate the contributions of CD and MD variability of sheet properties to those recorded by an on-line scanner provided improved estimates of the locations of CD variability. The use of bump tests to identify the mapping between actuator settings and the location of their influence in the reel is well established and improved techniques for the use of such data to improve estimates of CD actuator alignment and hence shrinkage are described by Gorinevsky, Heaven et al. [8,9]. These techniques differ from the method described here in that they do not use slice opening or dilution actuator information and are at present unsuitable for continuous real-time monitoring.

There is considerable CD shrinkage also in the manufacture of extruded plastic films. This differs from the shrinkage of paper in that it is almost entirely mechanical in nature and CD actuator settings may be controlled by considering a mass balance on the mass per unit area of the film. Whilst a simple material balance could be applied to determine the shrinkage profile on a papermachine if the values of all variables were known, this is rarely the case and variations exist locally as well as globally. In papermaking, mechanical shrinkage is coupled also with hydro- and hygroscopic shrinkage. Separation of these effects is non-trivial and the subject of ongoing study at UMIST; for discussion of mechanical shrinkage effects, see Wahlström et al. [10].
If a number of assumptions are accepted, then it is readily shown that the slice, or dilution, actuator profile is a function of the corresponding grammage profile and the CD shrinkage profile; the relationships among CD actuator settings, the grammage profile on the wet end and the dry-line on a Fourdrinier table is discussed by Kjaer [11]. Here we present these assumptions and justify their use to allow derivation of expressions that allow data describing the deflections of the slice-lip of a traditional headbox to be used to estimate the shrinkage profile of the paper machine. Data from the literature are used to demonstrate the applicability of the theory. Given a simple change of variable, the technique is suitable for application to machines running dilution controlled headboxes.

Theory

Consider first a strip of paper dried under tension in the machine direction. The mass of fibre in the strip is unaffected by drying, but its area and hence its grammage, \( W (g\text{m}^{-2}) \) are affected by the strain in the machine direction and the amount that the strip shrinks in the cross direction. For a fractional machine direction strain, \( E \) and fractional CD shrinkage, \( S \), the change in grammage \( \Delta W (g\text{m}^{-2}) \) is given by:

\[
\Delta W = \frac{1}{(1-S)(1+E)}
\]

such that the grammage of the sheet will increase, \( i.e. \Delta W > 1 \) if \( S > E/(1-E) \). On a papermachine, the machine direction strain corresponds to the total draw along the machine and is typically less than 5 \%; accordingly we may state, to a first approximation, that sheet grammage will increase if the shrinkage is greater than the total draw.

Now, the \textit{vena contracta} is defined as the position in front of the slice opening at which the jet has maximum speed and minimum thickness and the efflux ratio, \( \varepsilon \) is defined as the speed of the jet divided by that of the wire. The contraction coefficient of the jet, \( \mu \) is defined as the thickness of the jet at the \textit{vena contracta} divided by the height of the physical slice opening. We assume that these characteristics of the headbox and the jet are constant across the width of the machine; in the forming section, we assume that the mass consistency of the jet, \( C (%) \) and the fractional first pass retention, \( R \) are constant across the width of the machine also. In practice, cross-flows occur between elements of the suspension delivered from adjacent locations in the cross-direction [8,9]; here we assume that each actuator influences a discrete element of the paper at the reel; the result being a low-pass filtering of the resultant shrinkage profile.

Consider now a headbox where cross-machine grammage control is achieved by an odd number of actuators across the slice lip separated from each other by a uniform interval, \( a (m) \). In the derivation that follows, parameters that vary across the width of the machine are denoted by variables with a subscript, \( i \) denoting its location and \( i = 0 \) denotes the location of the central actuator. Thus, for example, the slice opening at the location
of the $i$th actuator is denoted $D_i$ and that of the central actuator is denoted $D_0$. The notation is illustrated for a headbox with $n$ actuators in Figure 1 where an element of the suspension delivered from an actuator of width $a$ is subject to shrinkage after the forming section such that it has width $x_i$ depending on its location; the ratio of each $x_i$ to $a$ defines the shrinkage at that location. We assume that the shrinkage profile is broadly symmetrical about the central point of the dry paper such that fibre delivered at the centre of the headbox jet is located at the centre of the machine reel.

If the slice opening at the central actuator is $D_0$ (mm) then the oven-dry grammage of the sheet at the central point of the reel, $W_0 (g \, m^{-2})$ is given by

$$W_0 = \frac{\mu D_0 \, C \, R \, E}{(1 - S_0)(1 + E)} \quad (3)$$

where the numerator represents the grammage retained on the wire for this central location.

The location in the reel of fibre delivered from positions either side of the centre of the headbox will depend on the shrinkage at this location and that of the sheet between this position and the centre. We consider first the dependence of the grammage delivered at each location across the width of the headbox. Given this, we may determine the location of fibre in the reel relative to its position when delivered from the headbox and hence may estimate the shrinkage profile.

The oven-dry grammage of the paper delivered from the $i$th actuator is given by:

$$W_i = \frac{\mu D_i \, C \, R \, E}{(1 - S_i)(1 + E)} \quad (4)$$

We note that Equation (4) assumes that the stock speed on leaving the slice is constant, i.e. it is unaffected by the slice opening, such that the mass of dry material leaving the slice at any point depends on the slice opening only. The total draw, or the increase in length of the paper as it is pressed, dried and reeled, is assumed to be constant across the machine also.

The shrinkage experienced by the fibre delivered from the $i$th actuator relative to that at the centre of the machine is given by,

$$S_i' = \frac{\mu(D_0/W_0 - D_i/W_i) \, C \, R \, E}{1 + E}. \quad (5)$$

For a given furnish and machine conditions, the shrinkage profile is rather stable and the grammage profile across the machine is usually fairly constant; the latter being, after all, the purpose of the deformable slice lip and grammage control loop. When this is the case, $W_i = W_0 = W$ and Equation (5) becomes,

$$S_i' = \frac{\mu(D_0 - D_i) \, C \, R \, E}{(1 + E)W}. \quad (6)$$

This is important as it means that we need to know only the relative deflections of the actuators, rather than the precise slice-lip opening.

Applying Equation (6) for all $i$ allows determination of the mean shrinkage taken over all actuators, $\overline{S}$ and the shrinkage relative to the mean dimension of the dried paper for the fibre delivered from each actuator location is,

$$S_i'' = \overline{S} - S_i'. \quad (7)$$

If we know also the mean shrinkage of the whole web, $S_{tot}$, then the absolute shrinkage of fibre delivered at the location of the $i$th actuator, $S_i^{abs}$ can be calculated using the expression,

$$1 - S_i^{abs} = (1 - S_i'')(1 - S_{tot}). \quad (8)$$

Note that Equation (8) does not state that absolute shrinkage at any point is given by the sum of the relative shrinkage at that point and the total shrinkage, but instead is given by,

$$S_i^{abs} = S_i'(1 - S_{tot}) + S_{tot}. \quad (9)$$

Knowing the absolute shrinkage experienced by fibre delivered at a given location across the slice allows determination of its location in the reel. Recall that that fibre delivered at the location of the central actuator is assumed to be located in the centre of width of the reel. Let the $i$th element of the sheet be that delivered from a width of the slice $\pm a/2$ (m) from the location of the $i$th actuator. From Equation (9) and referring back to Figure 1, the distance, $x_i$ (m) of the centre of the $i$th element of the sheet from the centre of the width of the reel is given by,

$$x_i = x_{i-1} + \frac{a}{2} \left( S_i^{abs} + S_{i+1}^{abs} \right). \quad (10)$$

On many modern headboxes, dilution actuators that vary the consistency of the stock across the headbox are used to control the grammage profile. Here the situation is similar and Equation (4) for the oven-dry basis weight of the element of paper corresponding to actuator $i$ becomes,
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content at reel up</td>
<td>9 %</td>
</tr>
<tr>
<td>First-pass retention, $R$</td>
<td>60 %</td>
</tr>
<tr>
<td>Total draw, $E$</td>
<td>3 %</td>
</tr>
<tr>
<td>Consistency, $C$</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Contraction ratio, $\mu$</td>
<td>0.7</td>
</tr>
<tr>
<td>Efflux ratio, $\varepsilon$</td>
<td>1.03</td>
</tr>
<tr>
<td>Calibration coefficient, $K$</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table I: Assumed values of parameters

\[
W_i = \frac{\mu D C_i R \varepsilon}{(1-S_i)(1+E)},
\]

such that Equation (5) for the CD shrinkage profile relative to the centre of the paper machine becomes,

\[
S_i = \frac{\mu(C_0/W_0 - C_i/W_i)D R \varepsilon}{1+E}.
\]

Again, we can often consider grammage constant across the width of the machine such that Equation (6) becomes,

\[
S_i = \frac{\mu(C_0 - C_i)D R \varepsilon}{(1+E)W},
\]

and subsequent expressions remain unchanged.

**Practical Application**

The algorithm described above is suitable for implementation for on-line monitoring of shrinkage profiles that are continually updated in response to changes in slice or dilution control actuators, draw, total shrinkage, retention and mean headbox consistency. Many of the variables are typically measured regularly and automatically as part of the control and monitoring systems; others, for example total shrinkage, may only be measured intermittently and could be updated as they become available. As presented, the theory assumes that the active width of the slice extends to a point halfway across the last slice-lip actuator in use, i.e. the one nearest the edge of the machine. In reality, the position of the forming section trim jets is certain to be somewhere within the width controlled by the last actuator; this can be determined by inspection of the machine.

For initial setting-up and calibration purposes, a CD shrinkage profile measured in the established way using forming fabric marks would be required. If this did not match the uncalibrated profile, then this is likely to be due to an error in the input values of consistency, first-pass retention or total draw that are required as inputs to Equations (6) and (13). Such errors are typically difficult to find and are likely to be systematic; though differences would still be accurate. For calibration, errors in the values of these parameters can be corrected by multiplying by a calibration constant, $K$ determined to make the profiles coincide. Thus, Equation (6) becomes,

\[
S_i = K \frac{\mu(D_0 - D_i)C R \varepsilon}{(1+E)W},
\]

and Equation (13) becomes,

\[
S_i = K \frac{\mu(C_0 - C_i)D R \varepsilon}{(1+E)W}.
\]

We expect parameter $K$ to take account of the speed difference between the fibre suspension and the forming fabrics, as determined by the machine speed, the efflux ratio and the acceleration of the stock on leaving the slice; these in turn determine the location of the *vena contracta* beyond the slice-lip. When the number of actuators is even, the parameters at the central point may be determined as the average of the central pair and the displacements of actuators either side of these altered accordingly.

**Example**

Phillips *et al.* [6] present data for the slice-lip deflection and shrinkage profile for the same paper machine making 45 g m$^{-2}$ newsprint and showed that both profiles could be fitted to the same type of function. Although the profiles were not obtained at the same time, shrinkage profiles are fairly stable and it is reasonable to expect that some correspondence would exist between the measured shrinkage profile and one estimated using the slice-lip deflections.
Discussion and Conclusions

Theory has been presented that allows a good estimate of the cross-directional shrinkage profile to be obtained from the profile of actuator settings for slice-lip deflection or dilution control headboxes. Despite the use of several simplifying assumptions, application of the theory to data from the literature shows the technique to give a sensible estimate of the shrinkage profile. As such it is suitable for application on paper machines utilising existing and available data to allow monitoring of shrinkage profile in close to real-time.

Whilst there are a number of possible sources of error, most of these can be corrected for by a one-off calibration against a laboratory measurement of CD shrinkage profile. Since the theory links the settings of headbox actuators directly to the grammage and shrinkage of the sheet, it follows that it yields also the mapping between actuator settings and the location of their influence in the reel.

Our treatment neglects the influence of the cross-flows that occur between the suspension delivered from the locations adjacent actuators and as such we effectively apply a low-pass filter to the data and smooth out local variations in the profile. Ongoing work seeks to improve the quality of the estimate by removing some of the assumptions used here and accounting for phenomena such as cross-flows and identifying the genuine location of the true centre of both the shrinkage and headbox profiles.

Acknowledgements

This work was funded by the member companies of the UMIST Shrinkage Research Consortium: Aylesford Newsprint Ltd., M-real Corporation (New Thames Mill) and Voith Fabrics Blackburn Ltd.
References

The measurement of differential CD shrinkage

Differential shrinkage of paper in CD

Dried-in shrinkage profiles of paper webs


Method for recognition of Shrinkage using Image Processing

CD Shrinkage Profiles of Paper - Curve Fitting and Quantitative Analysis.

[7] S.-C. Chen
Full-width sheet property estimation from scanning measurements.

New algorithms for intelligent identification of paper alignment and nonlinear shrinkage

Integrated tool for intelligent identification of CD process alignment, shrinkage and dynamics.

Numerical modelling of the cross direction shrinkage profile in a dryer section, a first approach.

Modelling, sensing and identification of web-forming processes.