Web instability in the open draw and the impact on paper machine efficiency

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ABSTRACT: Paper is most likely to break in the first open draw on a paper machine where it is unsupported, wettest, and weakest. Tension is applied to peel the web from the roll surface, as well as minimize web flutter in the open draw. The average tension is well below the breaking point and is often set by adjusting the speed difference between the press and the next machine element by visually observing the behavior of the web. However, machine direction variations caused by instabilities in the paper machine can cause tension swings that exceed the strength of the web.

Measurement of the web's release point from press rolls on pilot and commercial paper machines was used to identify the cause of tension instabilities. Variations in the speed of the paper machine drives and the work of adhesion from the press roll surface were identified as key factors. Fluctuations of paper moisture, which affects the elastic modulus and strength of the web, appear to be less important.

Application: Measurement of the release point of the web from a press roll can be used to identify tension stability problems in the open draw and the source of web breaks. Paper machine drive stability and the web adhesion to the press roll surface are possible problem areas.

Web breaks on paper machines commonly occur in the first open draw where paper is wettest and weakest. The strength of the web in the first open draw is a critical factor in determining ultimate machine speed and therefore production. A key principle of new machine design has been to move the open draw farther down the machine, where the web is drier and stronger. This has been accomplished using pick-up felts at the couch and clustering press rolls to support the web through two or three press nips. In modern paper machines, the first open draw is typically between the last press and the dryer. For lightweight grades such as tissue, the web is entirely supported until it is dry-creped off the yankee dryer. For some heavier grades, the draw between press section and dryers has been closed on a few machines using transfer felts or belts [1-3]. Another approach has been to reduce moisture content before the first open draw by shoe presses. Despite these advances, many paper machines today still have an open draw between the last press and the dryer. Consequently, there remains a need to mitigate web breaks in this zone.

Because webs adhere to press rolls, tension must be applied to peel the web from the roll surface. Web adhesion to the press roll is a function of surface topography and chemistry, as well as operational factors such as web solids, temperature, and paper machine speed [4-8]. Online tension measurements on a pilot press [4] and pilot paper machines [9-11] have been used to study the behavior of the web in the open draw and calculate the work of adhesion under commercial conditions.

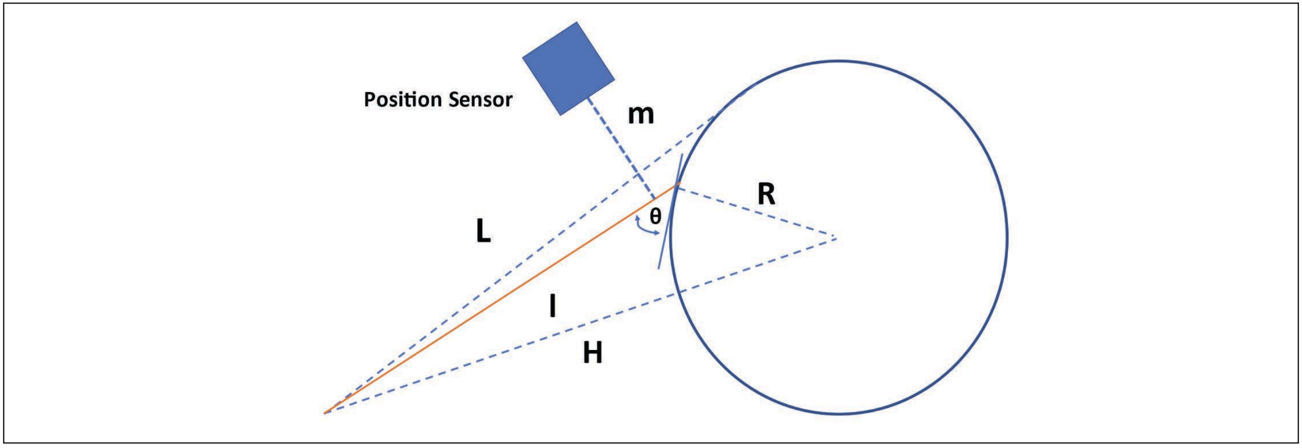
Given the importance of the open draw on paper machine operation, several theoretical models have been proposed [12-16], but they remain to be confirmed by experimental studies. For example, Edvardsson and Uesaka [16] showed the critical importance of the release point and its sensitivity to operational and material variations, but this is yet to be demonstrated under commercial conditions.

A laser camera has been used on a commercial paper machine to measure the distance between a fixed point and the web position near the release point from a press roll [7]. This distance was used to measure the effect of draw, basis weight, furnish composition, and chemistry on the web's behavior in the open draw [7]. In our study, we have extended this technique by deriving equations that relate this distance to strain and tension in the web. This technique has been used on pilot and commercial paper machines to identify and rectify the cause of disturbances that can lead to web breaks.

ANALYSIS

Breaks occur when web tension exceeds web rupture strength. Tension and variation in tension are difficult to measure on operating paper machines. To overcome this, we have taken an indirect approach based on the following picture of cause and effect.

The primary operating variable in this problem is web draw (stretch, [%]), attained by setting differential roll speeds. In practice, draws are set to provide a suitable tension often well below the average breaking point of the web, to avoid web flutter and instabilities. In addition to



1. A laser position sensor was used to measure the distance to the web in the open draw. The measurement can be used to calculate the release angle, θ, and release point. This configuration is for the open draw between the third and fourth press on the FPInnovations pilot paper machine. The draw length is l, R is the radius of the press roll, H is the distance from the center of the press roll to the next stage, and L is the maximum possible draw length.

draw, tension is governed by the web modulus E and thickness t:

$$T = Et\varepsilon \quad (1)$$

Web tension and work of adhesion, W, set the angle of release, θ, according to the Rifkin equation (first term in Eq. 2). At high speeds, an additional force is required to turn the web at the peel point. This force is determined by the web mass per area, M, and the speed of the machine, V. The resulting peel equation is:

$$T = \frac{W}{1-\cos\theta} + MV^2 \quad (2)$$

For this tension, the web self-positions on the roll to give the required release angle θ in Eq. 2. This release point sets the length of the draw, l, to a fixed-point downstream point (for example, the nip of first dryer), as shown in **Fig. 1**. For the machine speeds considered in this paper, the MV^2 term is second order and was not included in subsequent calculations. Above 2000 m/min, which is higher than that of the fastest machines with an open draw before the dryers, the MV^2 term becomes important and may be a barrier to higher machine speeds.

In typical operation, angle θ is small, and changes in this angle are sufficiently small to be described by derivatives such as $d\theta$ and dT. These can be calculated by measuring the change in distance dm near the release point (Fig. 1).

The change in the release angle expressed in differential form is:

$$d\theta = \frac{-\theta^3}{4W} t(Ed\varepsilon + \varepsilon dE) + \frac{\theta}{2W} dW \quad (3)$$

The effect of $d\theta$ on dT is given by:

$$dT = \frac{-W\sin\theta}{(1-\cos\theta)^2} d\theta + \frac{1}{(1-\cos\theta)} dW \approx \frac{-4W}{\theta^3} d\theta + \frac{2}{\theta^2} dW \quad (4)$$

We note that the previous equations can also be expressed in terms of time derivatives

In this study, angle $d\theta$ is calculated from the measured change in distance of the web near the release point, dm, as shown in Fig 1. The relationship between dm and $d\theta$ is derived in the Appendix:

$$d\theta = \frac{dm}{l[1+\frac{R\theta}{L}]} \quad (5)$$

The sensor and setup employed to measure dm is described in the following section.

EXPERIMENTAL PROGRAM

Measurements of dm were made on the presses of a pilot paper machine and on two commercial machines using a displacement sensor accompanied by measurements of moisture content and draw.

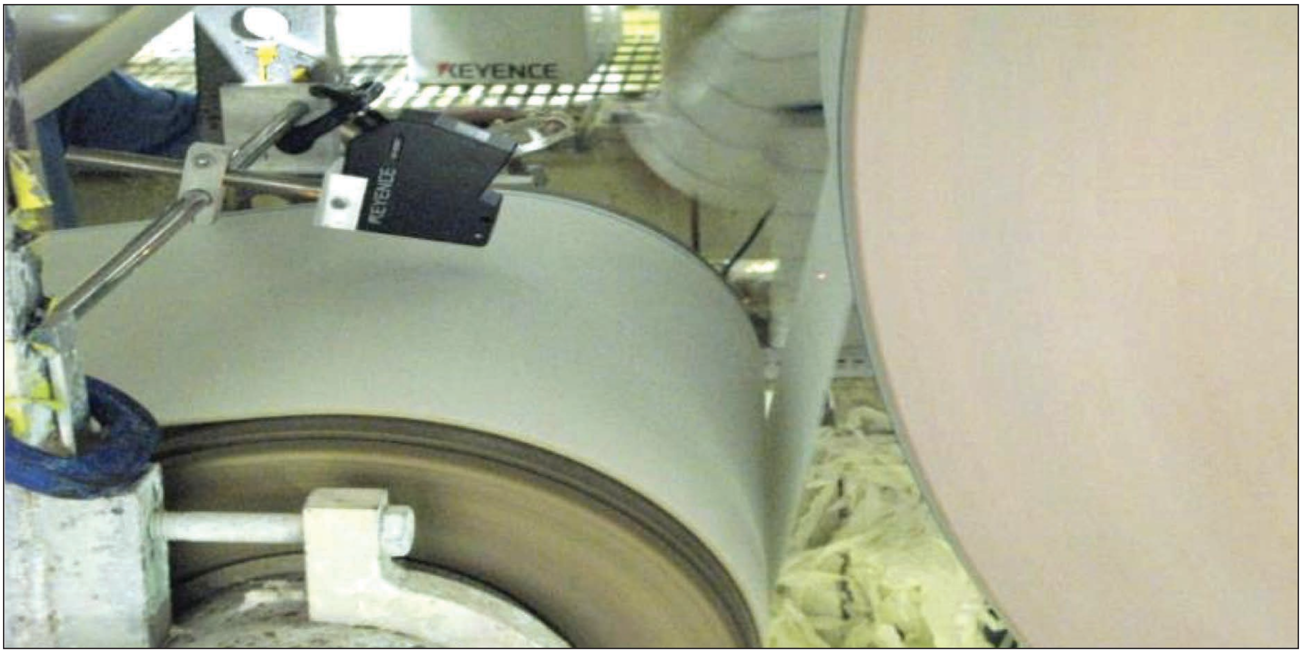
Equipment

Position sensor

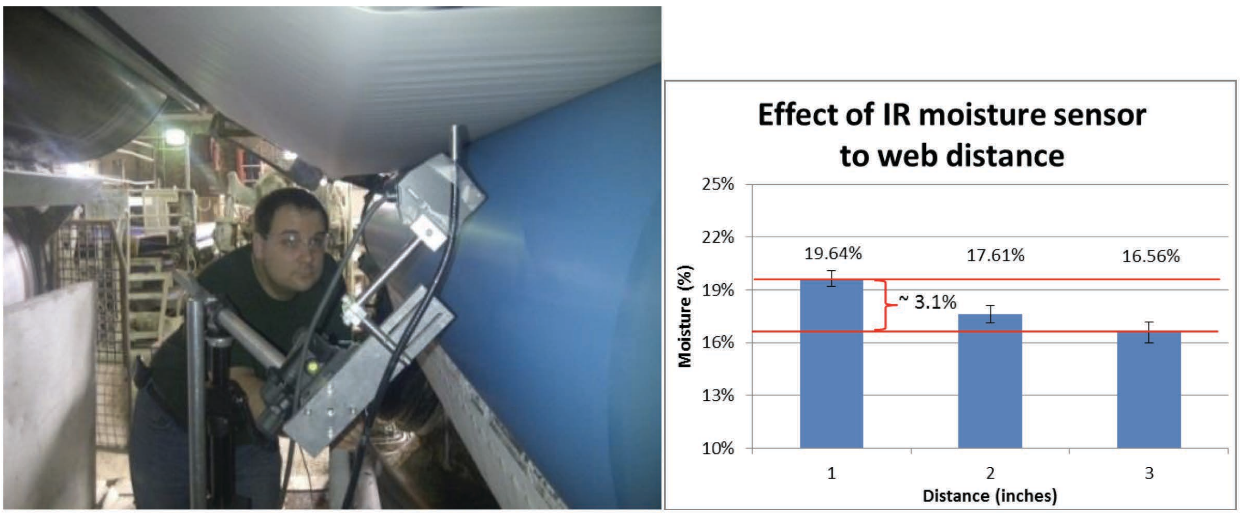
The position sensor is a charge coupled device (CCD) long-range laser displacement sensor, the Keyence LK-G150 (Keyence; Osaka, Japan). It has high resolution (0.5 um) and high accuracy (±0.05%). The position sensor is aimed at a fixed point on the web near the release point, as shown in **Fig. 2**.

Portable solids content sensor

Local moisture content was measured with a portable IR sensor (MCA 1420, Fibro System; Stockholm, Sweden). Because its output depends linearly on distance from the web,



2. The position sensor aimed near the web release point on the third press of the FPInnovations pilot paper machine.



3. Portable infrared moisture sensor positioned in the open draw of a commercial fine paper machine. Shown also is the effect of distance between the sensor and paper surface on moisture measurement.

as shown in **Fig. 3**, it was situated next to the position sensor. Simultaneous measurement of distance and moisture permitted a linear correction to account for changes in distance.

Speed sensor

A contactless laser speed sensor (Beta laser, NDC Technologies; Dayton, OH, USA) based on Doppler frequency shift was used to measure web speed (**Fig. 4**). The speed difference from two sensors before and after a press nip were used to calculate the draw.

Test program

Effect of drive instability: pilot paper machine

This work was carried out on the FPInnovations pilot paper machine, which is described elsewhere [17]. Measurements were made between the third and fourth press during periods of good and poor stability (breaks). **Figure 5** shows the time-varying draw and release point. The two discontinuities in the latter signify breaks. There was little variance in the moistures, but significant variance in the draws. The problem was traced to vacuum fluctuations in the uhle box that caused the speed of the

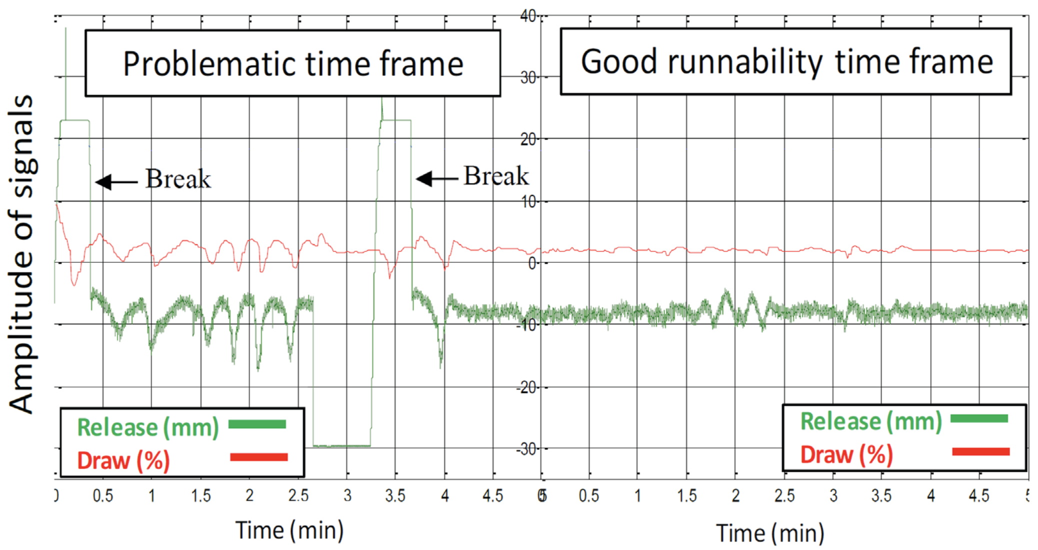
4. Non-contact laser speed sensor for velocity measurement.

fourth press felt and hence the press to vary.

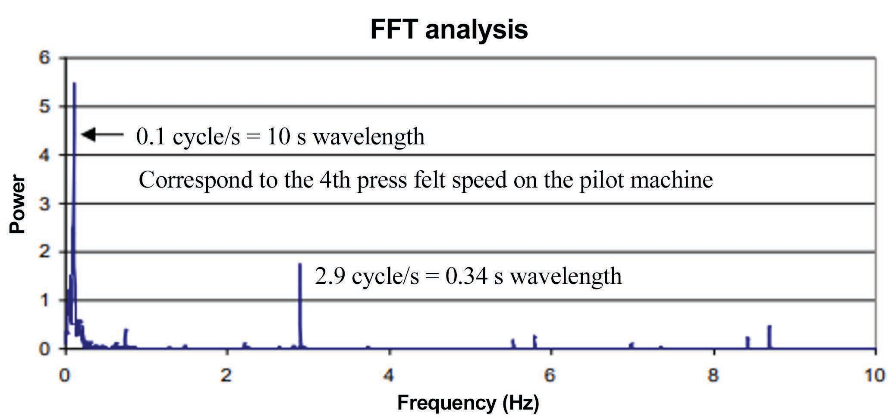
A frequency analysis shown in **Fig. 6** confirmed that the vacuum fluctuations had the same frequency as the release fluctuations. Once the uhle box problem was corrected, release variations were eliminated and so were breaks, as shown for the good runnability case in Fig. 5.

Effect of drive instability: mill press section

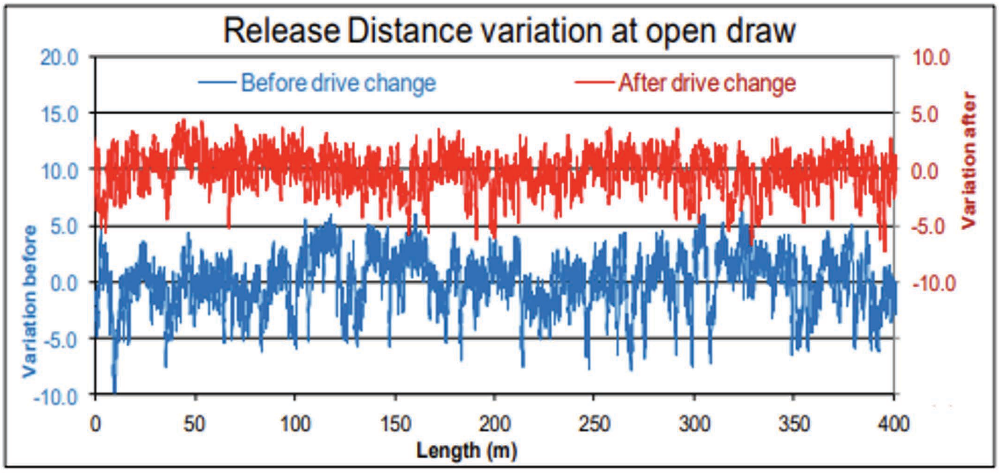
In this case, a fine paper machine experienced breaks in the open draw, but the cause was unclear. Our measurements indicated that moisture content was stable, but there were significant variations in release angle. This suggested draw variations. The source was diagnosed to be the flywheel on the drive after the couch. Replacing this flywheel reduced the release angle variations by 55%, as shown in **Fig. 7**. Consequently, draw variations and web breaks were reduced.



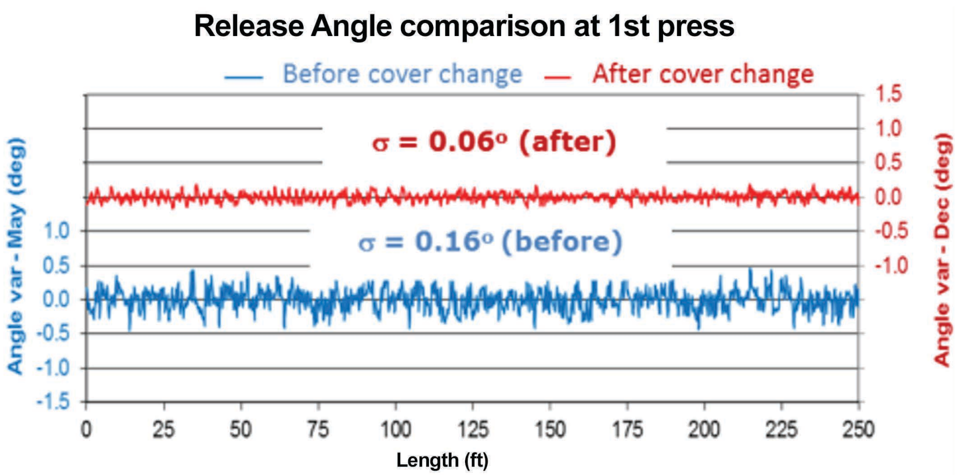
5. Measurements of release point and draw on a pilot paper machine during periods of poor and good runnability.



6. Fast Fourier transform (FFT) frequency analysis of release angle measurement shows cyclic variations caused by malfunctioning uhle box.



7. Release point variation was reduced after changing the drive flywheel by reducing the drive speed fluctuations.



8. Replacing the press roll cover reduced the release angle variation.

Effect of work of adhesion

Work of adhesion, *W*, plays a key role in the link between release angle and tension (Eq. 2). Each roll cover has a unique value of *W* that can change over periods of time as the roll is worn or cleaned.

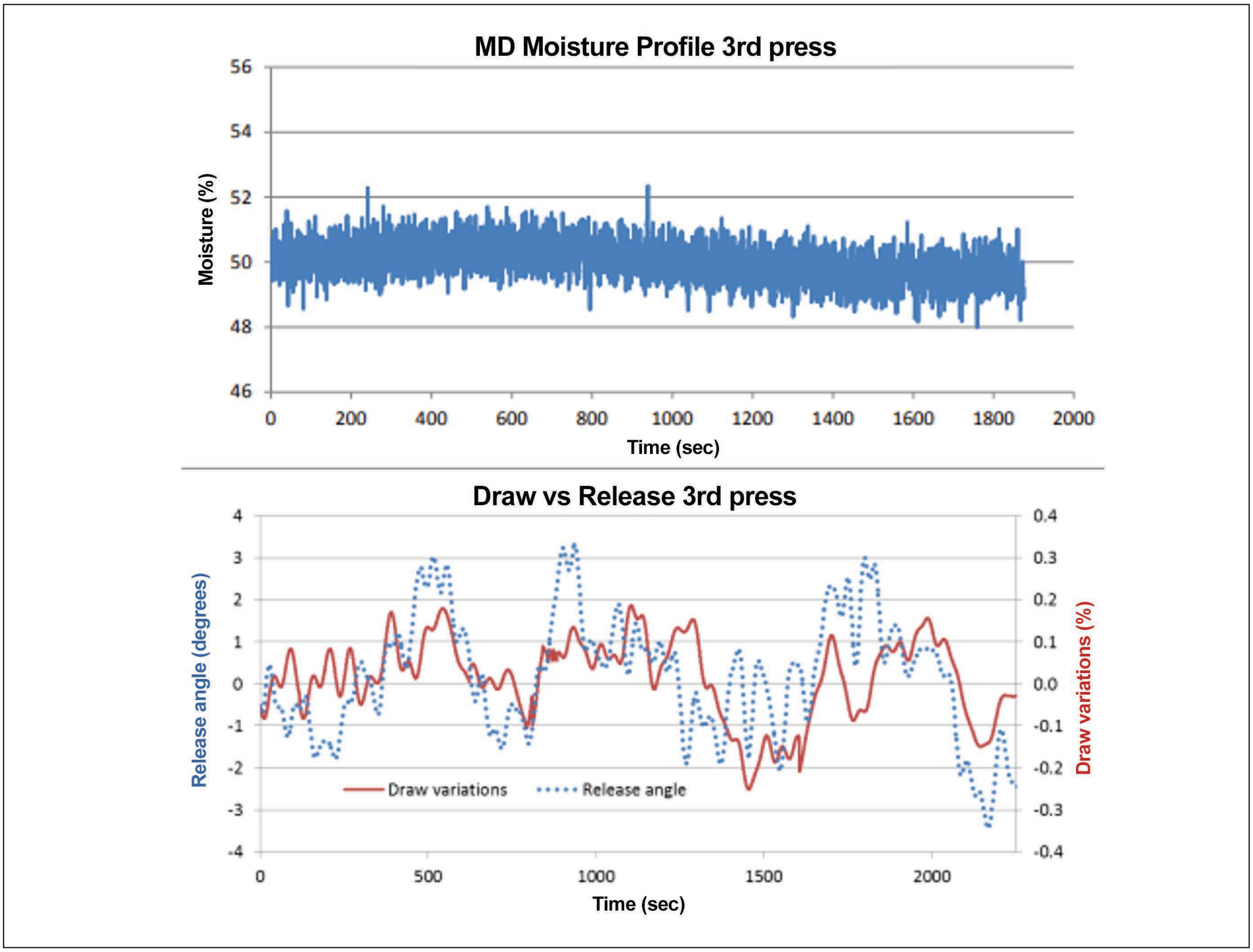
A fine paper machine was experiencing over 20 breaks per day at the first press open draw. The mill made a number of changes in the wet end, including replacing the cover of the first press roll, which significantly decreased the release angle variation, as shown in **Fig. 8**. There are two possible reasons for this outcome. First, a larger work of adhesion would reduce the release point variation caused by unsteady draw or moisture (first term in Eq. 3). Second, fewer sticky deposits that cause uneven stick/release would also reduce release point variation (second term in Eq. 3). Our measurements did not allow us to distinguish between the two mechanisms.

There was also a small decrease in moisture variability, but this was not correlated with draw variability.

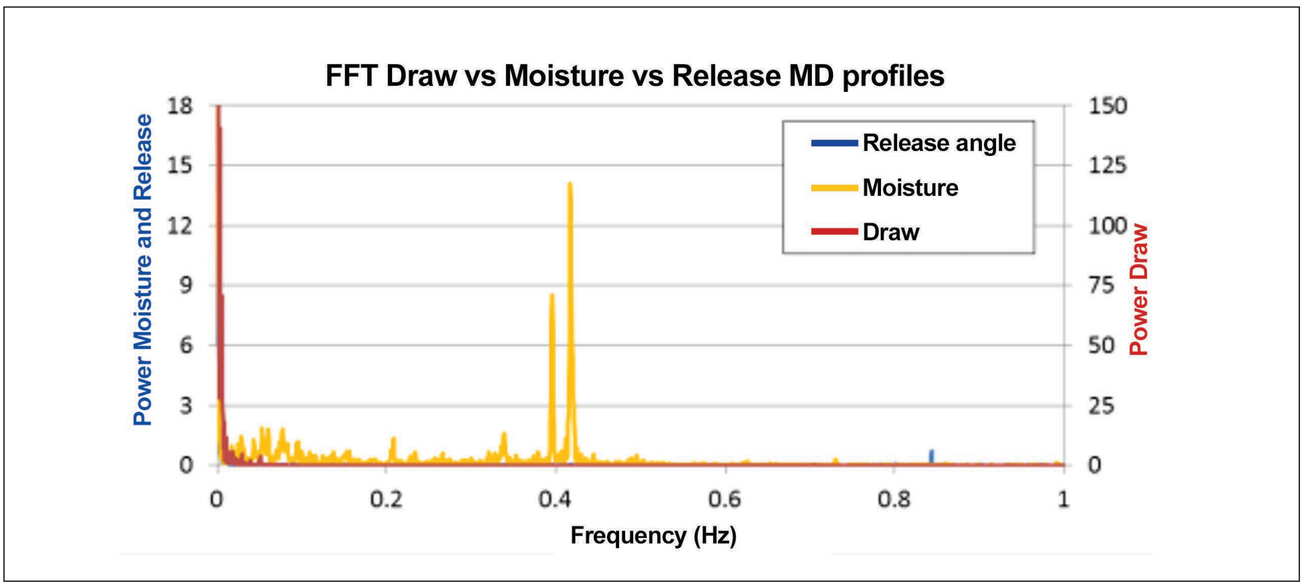
Effect of web modulus of elasticity

Machine direction modulus governs the relationship web between tension and draw. Moisture content is a major factor determining modulus, but the relationship is complex, depending on speed and draw size. Measurements on the fine paper machine shown in **Fig. 9** and **Fig. 10** exhibited no correlation between draw and moisture, perhaps because the moisture changes were too small to produce measurable changes in draw and release angles.

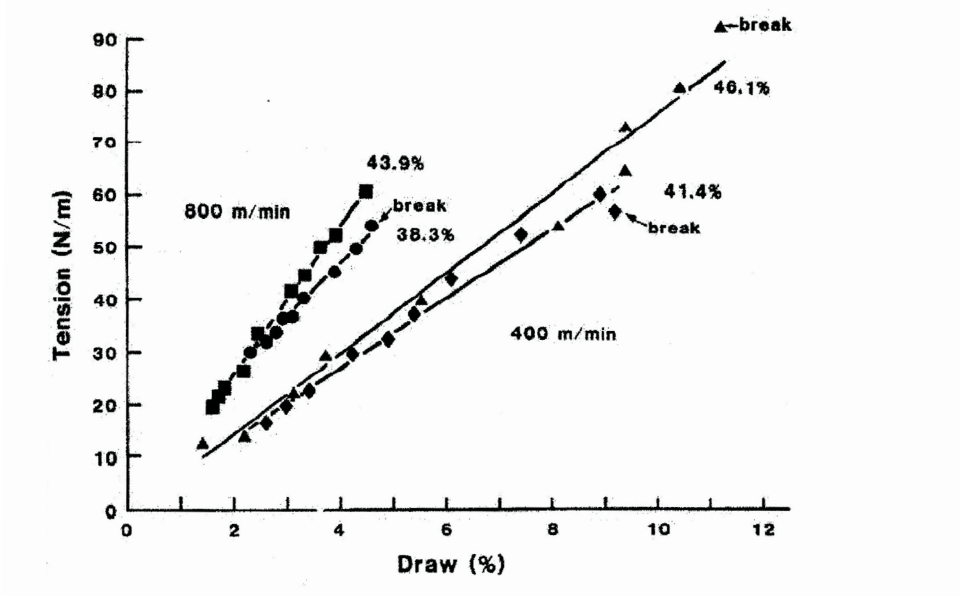
Web moisture will affect machine direction modulus, but determining this relationship is challenging. The modulus of wet webs is speed dependent, and reaching commercial machine speeds in laboratory measurements is difficult. To address this issue, we used tension vs. draw



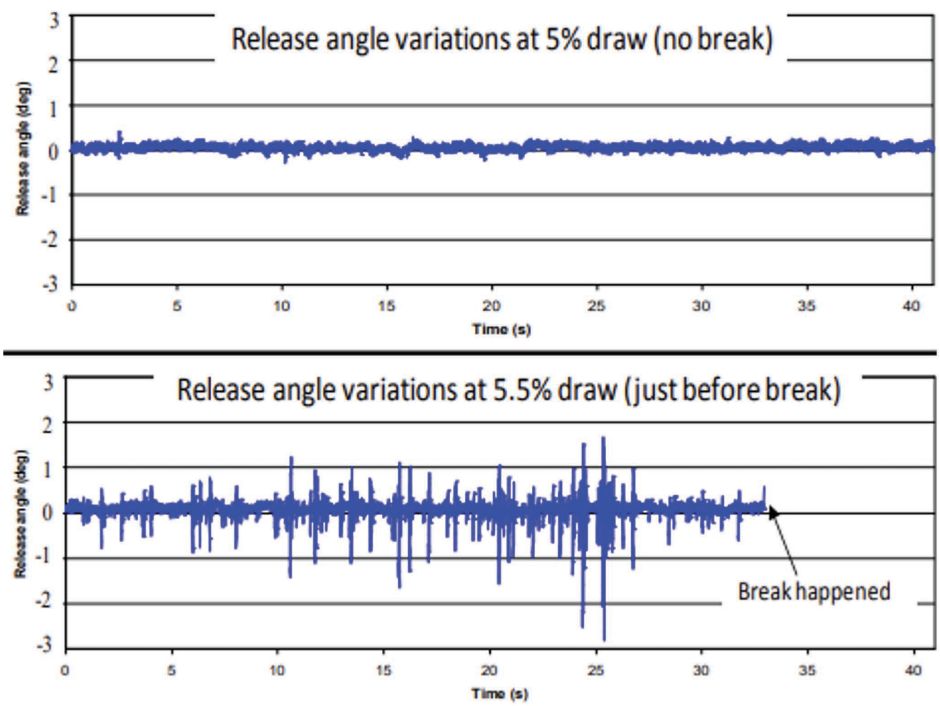
9. Draw and release angle in the open draw after the third press on a fine paper machine. The draw and release angle follow a similar pattern, as expected from Eq. A4 in the Appendix. The variation in machine-direction (MD) moisture does not affect the release angle or draw.



10. Frequency profiles for MD moisture, release angle, and draw after the third press on a fine paper machine. The cyclic variations in moisture do not appear in the release angle or draw.



11. Pilot machine measurements of tension and draw for a newsprint furnish [11].



12. Release angle variations in the first open draw on the FPInnovations pilot paper machine increased dramatically when the draw was increased from 5% to 5.5%.

measurements from a pilot paper machine for a newsprint furnish to determine the modulus at several different conditions [11]. As shown in **Fig. 11**, increasing the paper machine speed or increasing the web solids increases the slope of the tension vs. draw lines, which is proportional to the web modulus (Eq. 1).

The relative effect of draw vs. moisture variation on the web tension at 800 m/min is shown in the following calculation. In Fig. 11, the slopes of the tension vs. draw lines are 11.8 N/m and 13.3 N/m for web solids of 38.3% and 43.9%, respectively. Consider a draw of 3.5%, which is safely below the breaking point of the web, at an average moisture of 44%. In Fig. 9, the draw variation is 0.4%, which would cause a tension variation of 5.3 N/m. On the other hand, the moisture variation was 2%, which would cause the tension to change by 1.8 N/m. This means that the effect of the moisture (modulus) change on draw or release point is below the detection limit of the equipment. This explains why the measured variation in web moisture does not appear as a variation in Figs. 9 and 10. However, potentially larger variations in moisture caused by press barring or by variations in basis weight could cause measurable changes in release point or angle. However, these variations would cause greater problems than draw and tension variations.

Effect of draw

The effect of draw was also studied on the pilot paper machine. As shown in **Fig. 12**, increasing a draw from 5% to 5.5% significantly increased variations in the release angle and thereby tension. This value exceeded the threshold beyond which the draw became unstable and chaotic, displaying aperiodic variations in release point [18]. This higher tension combined with greater variability from the increased draw caused a break.

SUMMARY AND CONCLUSIONS

In the open draw of the press section, variations in draw, moisture content, and roll-web adhesion can lead to web tension instability and breaks. Measurements of the varying distance between the web near the release point and the press roll using a non-contacting sensor were used to calculate variations in release angle. This technique was demonstrated on a pilot machine and two commercial paper machines.

ABOUT THIS PAPER

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Large release angle variations and consequent web breaks were linked to speed-induced draw variations and web-roll adhesion changes resulting from a roll cover change.

This technique shows promise as a new tool to troubleshoot web breaks in the open draw of press sections. **TJ**

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ABOUT THE AUTHORS

We studied this topic because web breaks in the press section can have a significant impact on paper machine efficiency. Tension and web adhesion measurements to press rolls on high-speed pilot machines have shown that web breaks in the press section are the result of complicated, non-linear processes. Because web breaks are often infrequent events, monitoring must be done over long time periods to pinpoint the cause.

We discovered that paper machine drive stability and the adhesion of the web to the press roll surface are critical factors. Surprisingly, we found that although web moisture variation affects both paper modulus and strength, it appears to have a minimal effect on the web in the open draw.

For mills, measurement of the release point of the web from the press roll can be used to quantify instability in the open draw and as a tool to identify the source of the problem. This technique is available to help solve wet-end break problems on commercial paper machines.

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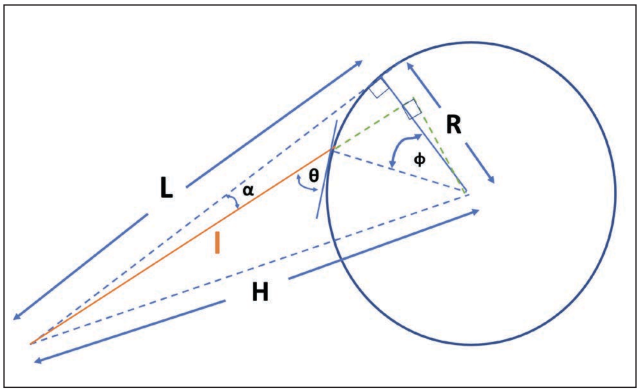
APPENDIX

Relationship between peel angle, release point, and draw length

Variations in peel angle and release point of a web from a press roll are indications of instability in an open draw. Here, we derive the relationship between peel angle and key factors affecting stability, such as draw, moisture content, and web tension. We then relate peel angle to the distance, dm, measured by the technique in this paper.

A generic open draw between a press roll and the next machine component is shown in **Fig. A1**. The radius of the press roll is R, and the distance from the center of the roll to the next machine element is *H*. The draw length is *l* and its maximum, *L*, is tangent to the press roll. As the peel angle increases from zero at the maximum draw length to π/2 radians at the point where *H* intersects the roll surface, the draw length decreases from *L* to *H-R*. The relationship between release point and release angle can be determined by extending *l* to form a right-angle triangle with a radial line, as shown in Fig. A1.



***A1. The draw length* l *is shown in orange. The maximum draw length* L *is tangent to the press roll surface. The distance between the center of the press roll and the downstream nip drawing the web is* H*. The release angle of the web from the roll is* θ.**

From geometry, the draw length is:

$$l = H\cos\left[\arcsin\left[\frac{R}{H}\sin(90-\theta)\right]\right] - R\cos(90-\theta) \quad \text{(A1)}$$

$$l = R\sqrt{\frac{H^2}{R^2} - [\cos\theta]^2} + R\sin\theta \quad \text{(A2)}$$

$$dl = R\cos\theta d\theta\left[1 + \frac{\sin\theta}{\sqrt{\left(\frac{H^2}{R^2} - [\cos\theta]^2\right)}}\right] \quad \text{(A3)}$$

For small peel angles, θ:

$$dl = R\left[1 + \frac{R\theta}{L}\right]d\theta \quad \text{(A4)}$$

The change in draw length is proportional to the change in peel angle and a factor consisting of roll diameter, maximum draw length, and angle of release.

Relationship between sensor measurement distance and peel angle

The sensor measures the change in distance *dm* to the web's surface near the release point.

$$dm = l d\alpha \quad \text{(A5)}$$

$$d\alpha = d\varphi = \frac{dl}{R} \quad \text{(A6)}$$

Substituting Eq. A6 into Eq. A4:

$$dm = l\left[1 + \frac{R\theta}{L}\right]d\theta \quad \text{(A7)}$$

The variation in the measured position of the web is proportional to the variation in peel angle and a factor consisting of the roll radius, maximum draw length, peel angle, and the draw length.

Factors that affect the release angle

In steady-state, the tension in the web is governed by Hooke's law:

$$T = Et\varepsilon \tag{A8}$$

and the Rivlin peel equation [19]:

$$T = \frac{W}{1-\cos\theta} \tag{A9}$$

where T is the tension, E is the machine direction modulus, ε is the strain, W is the work of separation of the web from the press roll surface, t is the thickness of the web, and θ is the separation angle.

For small changes in strain and modulus,

$$dT = t(Ed\varepsilon + \varepsilon dE) \tag{A10}$$

and release angle and work of separation:

$$dT = \frac{-W\sin\theta}{(1-\cos\theta)^2}d\theta + \frac{1}{(1-\cos\theta)}dW \tag{A11}$$

Substituting Eq. A10 into Eq. A11 gives an equation for incremental change in release angle:

$$d\theta = \frac{-(1-\cos\theta)^2}{W\sin\theta}\, t[Ed\varepsilon + \varepsilon dE] + \frac{(1-\cos\theta)}{W\sin\theta}dW \tag{A12}$$

For small release angles, where the average tension is large and the web is susceptible to breaking, Eq. A12 can be approximated by:

$$d\theta = \frac{-\theta^3}{4W}t[Ed\varepsilon + \varepsilon dE] + \frac{\theta}{2W}dW \tag{A13}$$

This assumes that the tension in the entire open draw changes instantaneously with changes in ε.

The variation of the release angle with time depends on the stability of the drives, the work of adhesion, and the MD modulus of the paper, which in turn depend on web moisture and thickness.