Influence of forming conditions on fiber tilt

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ABSTRACT: Fiber tilt describes the projection of fiber length in the thickness direction of paper. The projection is described by the tilt angle of fibers with respect to the plane of the sheet. A simple model for fiber tilt is based on jet-to-wire velocity differential in combination with cross-flows on the wire. The tilt angle of a fiber is found to vary as the sine of its in-plane orientation angle. The phase of variation is a large multiple of the fiber-misalignment angle associated with the cross flow. The multiple can decrease from 40 to 8 as the cross-flow angle increases from 1° to 10°, showing a high degree of nonlinearity. Application of the model was demonstrated by characterizing previously published tape-peels conducted at 45° intervals on both sides of a lightweight-coated base sheet. Degree of fiber pullout, a surrogate for fiber tilt, was indicated by measuring the mean gray value of images of the tape surface against a dark background. On tape peels from each side of the sheet, gray value versus angle was well described by a sine wave, but the phase of the wave was different on each side. By comparing the phases of the sine waves with those of the model, top and bottom fiber misalignment angles were calculated. The model is most sensitive to variations in misalignment angles less than 2.5°.

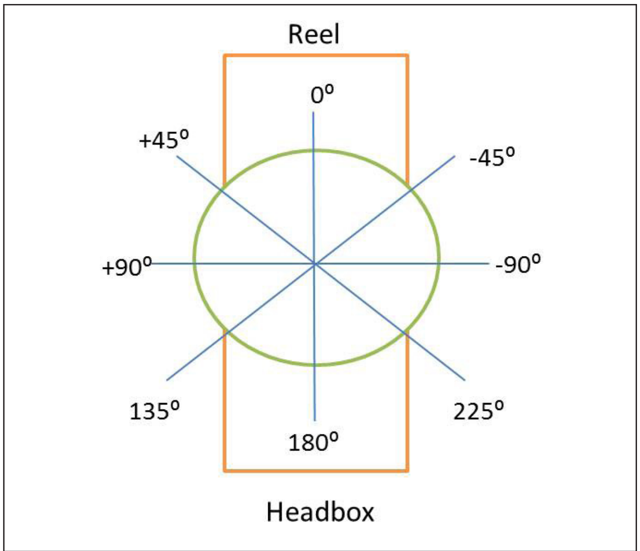
Application: The model could be a useful troubleshooting tool to complement two-sided fiber orientation measurements based on optical reflection. It could also help to explain the strength impact of tilted fibers when they bond multiple strata in the sheet.

Finger and Majewski showed that fibers flowing on a wire orient toward local streamlines that can, under certain circumstances, make a large angle with respect to the machine direction (MD) [1]. Drainage forces cause the leading end of the fibers to anchor in the existing fiber mat. The trailing end of the fiber may delay anchoring until other fiber layers have been deposited. In this manner, fibers acquire a z-direction tilt that allows them to bond with fibers occupying several layers. For example, a 200-µm fiber segment tilted at 5° can penetrate and potentially bond three paper strata, each 5-µm thick. Z-direction fiber tilt is highly differentiated from z-direction layering of stratified fibers that bond to each other where fibers "kiss" as in laminar solids, rather than cross and entangle.

Interest in this phenomenon has been focused on the possibility that tilted fibers in sufficient number and angle can help improve mechanical properties of the sheet [2-7]. Unfortunately, direct measurement of either their number or angle is problematic. Aaltio and Hermans used X-ray diffraction to measure an out-of-plane orientation factor for cellulose crystalline material in papers, not necessarily transferable to fiber tilt [8]. Hasuike et al. observed tilted fibers in microscope images of closely spaced paper cross sections (8 µm), but the volume examined was only 2000 μm^3 [4]. Synchrotron X-ray microtomography is promising for nondestructive examination of internal paper structures [9,10]; however, small voxels continue to prevent application of the information to commercial papermaking. Vahey et al. qualitatively demonstrated interior fiber tilt through directional studies of Scott Internal Bond strength and Brightness on a wide variety of samples [6]. Considine et al. demonstrated improved strength in eucalyptus handsheets that used small percentages of non-bonding carbon fibers to force eucalyptus fiber tilt [7]. In this case strength improvement was quantitative, but the number and tilt of fibers remained qualitative.

Directional tape peels are the simplest way to show the effects of fiber tilt. Some have followed the pioneering work of Finger and Majewski [1] in using them to demonstrate the existence of tilted fibers near paper surfaces [11] or to study the surface strength properties of paper [12-14]. Tape peels can be easy, fast and cheap. While they are not quantitative with respect to number and angle of tilted fibers, it is possible to look at the in-plane directionality of fiber pull-out using tape peel rosettes [1,11] and from them troubleshoot papermachine forming problems or study the relative effects of fiber tilt on z-directional strength properties. This work attempts to facilitate that goal by modeling the influence of forming parameters on the tendency of fibers to acquire tilt in a Fourdrinier process.

In the description of Finger and Majewski [1], based on drag conditions, the leading fiber end is lower in the sheet than the trailing end. A felt-side tape peel from the reel toward



1. Definition of angles, looking down on the web from the felt side.

MD, CD, ZD	Machine, cross-machine, and thickness directions
$\underline{J}$, J	Local jet velocity vector and magnitude
$\underline{W}$, W	Wire velocity vector and magnitude
β	Angle between $\underline{J}$ and $\underline{W}$
$\underline{\Delta W} = \underline{J}-\underline{W}$	Local rush-drag velocity differential
ΔW_0	Magnitude of rush-drag differential when β=0
ψ	Angle between $\underline{\Delta W}$ and *MD*
$\underline{L}$	Unit vector describing fiber in-plane direction
θ	In-plane angle between $\underline{L}$ and *MD*
θ_z	Tilt angle of fibers parallel to $\underline{\Delta W}$
$\Theta_z \le \theta_z$	Tilt angle of any fiber
$T[^o/\%]$	Tilt angle (θ_z) per percent of rush-drag velocity differential
$n \geq 1$	Exponent reflecting reduced fiber tilt at high rush-drag
$\Lambda[\mu m]$	Length of a representative tilted fiber segment
$\tau[\mu m]$	Thickness of a representative fiber layer
$N(\theta)$	Potential number of fiber layers bonded by a tilted fiber segment

I. Glossary of variables.

the headbox will skim over these fibers with minimal disruption to the sheet. A tape peel from the headbox toward the reel will scoop numerous fibers from the sheet to the tape. Under rush conditions, the leading fiber edge is again anchored closest to the wire side, but the free trailing edge can cartwheel over the anchored end, producing opposite results when directional tape peels are performed.

Finger and Majewski [1] and later MacGregor [11] published images of tape peel rosettes resembling the spokes of a wagon wheel made from tape peels at regular angular intervals. In [11], the intervals were 45° and peel directions spanned the full 360°, as defined in **Fig. 1**. An initially surprising fact is that significant fiber pullout can occur for tapes peeled in the cross-machine direction (CD) as well as the MD, since the rush-drag differential that drives fiber tilt ideally has no CD component. In the work of Finger and Majewski [1], tilt of CD oriented fibers was produced by the shake of a papermachine wire. In the case of MacGregor [11], the tilt of CD fibers was the result of cross flows on the wire. Even though the velocity associated with shake and cross flows was much less than machine velocity, they were comparable to the jet-to-wire velocity differential. This produced local streamlines with substantial CD directionality consistent with the observed tape pulls. The goal of this paper is to describe this effect for fibers pointing in any in-plane direction, given a general jet-to-wire velocity differential and cross-flow misalignment angle. For readers interested in the geometric-based model development to follow, a glossary of variables in **Table I** may prove useful.

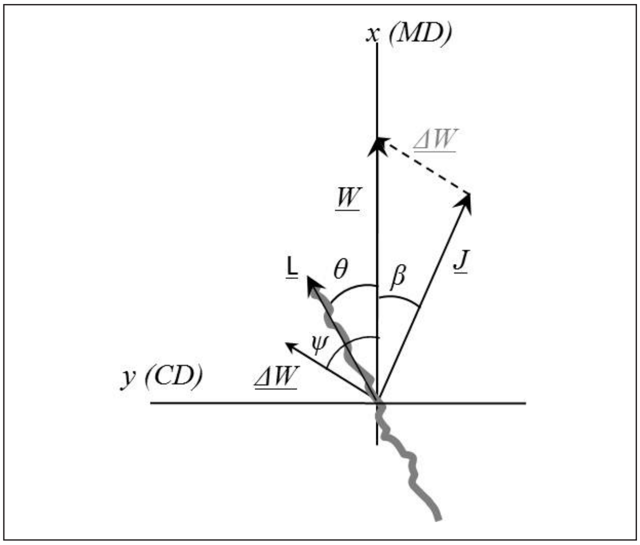
ANALYSIS

Consider wire velocity as seen by an initially untilted fiber traveling in a cross flow characterized by a misalignment angle β. This is an average cross flow experienced by the fiber over the time and space required for the fiber to become anchored in the fiber mat. Because many fibers will eventually align with the cross flow, it is comparable to the fiber misalignment angle frequently used for troubleshooting forming problems [11, 15-17]. Not all fibers will so align, and we consider a quasi-straight fiber that makes an average angle $\theta \neq \beta$ with respect to the MD, as shown in **Fig. 2**. A vector $\underline{J}$ (of magnitude J) indicates jet velocity experienced by the fiber, and a vector $\underline{W}$ (of magnitude W) indicates wire velocity. A person traveling with the center of gravity of the fiber would initially see the wire moving with a velocity $\underline{\Delta W} = \underline{W} - \underline{J} = [W\text{-}J\cos\beta, J\sin\beta, 0]$. This is the velocity associated with shear forces that drive fiber tilt. The smallest magnitude of $\underline{\Delta W}$ is $\Delta W_0 = |\underline{W} - \underline{J}|$, valid when $\beta = 0°$. This is nominally the rush or drag velocity differential of the process. For all non-zero values of β, the magnitude of $\underline{\Delta W}$ relative to ΔW_0 is the larger value given by Eq. (1):

$$|\underline{\Delta W}|/\Delta W_0 = \sqrt{1 + \frac{4JW}{\Delta W_0^2}\sin^2(\beta/2)} \quad (1)$$

In other words, the effective rush or drag of the process is amplified, and this amplification describes the potential enhancement of fiber tilt associated with cross flows.

The singularity at $\Delta W_0 = 0$ (equal jet and wire speed, or 0 rush-drag) is a reflection of low shearing forces at that condi-



2. Definition of angles and vectors used in the model. In this example, β is negative and θ and ψ are positive and L is a unit vector describing fiber in-plane direction.

tion, so that the mechanism driving fiber tilt is inactive. This situation is avoided in practical papermaking because the effects of forming-zone fluctuations are magnified, resulting in poor formation [18]. At values of rush-drag removed about 2% from wire speed, significant enhancement of the fiber-tilt mechanism begins to occur when cross-flow angles exceed 1°. The enhancement factor $|\underline{\Delta W}|/\Delta W_0$ can exceed 10 for β=10°.

Figure 2 shows the relationship between the fiber and the relative velocity vector $\underline{\Delta W}$ that drives fiber tilt. $\underline{\Delta W}$ has been translated to the origin of the coordinate system and assigned the angle ψ with respect to the MD. The formula for ψ in terms of jet, wire and cross-flow variables is Eq. (2):

$$\psi = \tan^{-1}\left(\frac{(J/W)\sin\beta}{(J/W)\cos\beta - 1}\right) \quad (2)$$

Note the convenience afforded by expressing ψ in terms of the jet-to-wire ratio instead of the nominal rush-drag differential, $\Delta W_0 = |\underline{W} - \underline{J}|$. Most of the predictions of the model are conveniently parameterized in terms of this ratio, and we will continue to use J, W, and J/W in equations along with ΔW_0 for ease of presentation. Keep in mind that J and W are comparable to each other and typically 50 times larger than ΔW_0, as when J/W=*0.98* (drag) or *1.02* (rush).

An offset $\Delta\psi$ = *180°* will be needed for most rush conditions in order to correctly place ψ in the quadrant occupied by $\underline{\Delta W}$. When the fiber direction characterized by unit vector $\underline{L}$ is within 90° of $\underline{\Delta W}$, as in Fig. 2, it experiences drag-like conditions in which drainage forces produce tilt downward toward the wire and reel. Notice that if the same fiber had been characterized by $-\underline{L}$, it could be said to experience rush conditions (being regarded now as more or less anti-parallel to $\underline{\Delta W}$) and tilt upward toward the felt side and headbox. The equivalent nature of these tilts shows independence of the choice of $\underline{L}$; however, the choice could be significant if it were used to indicate the direction of a felt-side tape peel, where a peel parallel to + $\underline{L}$ would produce significant surface disruption in comparison to a peel parallel to – $\underline{L}$. More surface disruption occurs when the moving tape-paper interface line passes first over the shallower end of the fiber, i.e., the end closer to the taped surface. Describing the fiber response to tape peel therefore requires an analysis spanning 360° as opposed to the customary 180° used for in-plane fiber-orientation analysis. This is recognized by the use of 360° tape-peel rosettes [1,11].

In the absence of detailed understanding of the fiber/shear/drainage interaction, the magnitude of tilt for fibers is modeled as proportional to the local rush or drag expressed as a percentage. This implies a tilt factor T with units of degrees per percent (°/%). For MD-oriented fibers moving in MD flows, the tilt angle is $\theta_z = -T \times 100\% \times (\Delta W_0/W)$. (Negative tilt is arbitrarily assigned for fibers tilting downward toward the wire and the reel.) For non-MD fibers in non-MD flows, the tilt applies only to the component of fiber length parallel to the flow vector $\underline{\Delta W}$, and the tilt increases by the enhancement factor, $|\underline{\Delta W}|/\Delta W_0$, given by Eq. (1). Although Eq. (1) allows indefinitely large enhancement factors, it is reasonable to speculate that the ability of shear forces to drive fiber tilt becomes less efficient as $|\underline{\Delta W}|$ increases over an order-of-magnitude range. To recognize this possibility in a reasonable manner that does not clutter the math, reduce the enhancement factor in Eq. (1) by taking its n^{th} root, where $n \geq 1$. Ultimately, justification of this choice awaits the ability to measure fiber tilt angles directly. For now, n is introduced to cover lack of knowledge about the complex hydrodynamic processes at work. The net result is the following expression for tilt angle θ_z, still applying only to the component of $\underline{L}$ parallel to $\underline{\Delta W}$:

$$\theta_z = -\mathrm{sgn}(\underline{L}\cdot\underline{\Delta W})100\%T\left|\frac{\Delta W_0}{W}\right| \times \left[1 + \frac{4JW}{\Delta W_0^2}\sin^2\left(\frac{\beta}{2}\right)\right]^{1/2n} \quad (3)$$

The key to the magnitude of tilt is the ratio $|\beta W/\Delta W_0|$. If the ratio is small compared to 1, the jet-to-wire velocity differential governs fiber tilt. For values much larger than 1, the cross flow angle β is the determining factor unless the attenuation exponent n is also large, in which case jet-to-wire differential continues to govern fiber tilt. An interesting intermediate case is $n = 2$, for which fiber tilt goes approximately as the geometric mean of the cross-flow angle and the jet-to-wire velocity differential.

Determination of θ_z does not complete the analysis. A general model for fiber tilt requires (1) describing an initially untilted fiber in terms of a wire-based coordinate frame with $\underline{\Delta W}$ defining the x' axis; (2) assigning a tilt to the x' component of the fiber vector $\underline{L}$ using Eq. (3); and (3) retransforming the (now) three vector components of the fiber length to the laboratory reference frame. The result is a simple formula for the tilt angle of a fiber having an in-plane orientation angle θ (Eq. [4]):

$$\Theta_z = \sin^{-1}\left[\cos(\psi-\theta)\sin\theta_z\right] \quad (4)$$

The in-plane fiber angles for which tilt has its extreme values are $\theta = \psi$ and $\psi+180°$, the phase ψ being described by Eq. (2). The extreme value of tilt at these angles is θ_z described by Eq. (3). Both angles ψ and θ_z depend on forming parameters β and J/W. In addition, θ_z depends on harder-to-know hydrodynamic factors T and n.

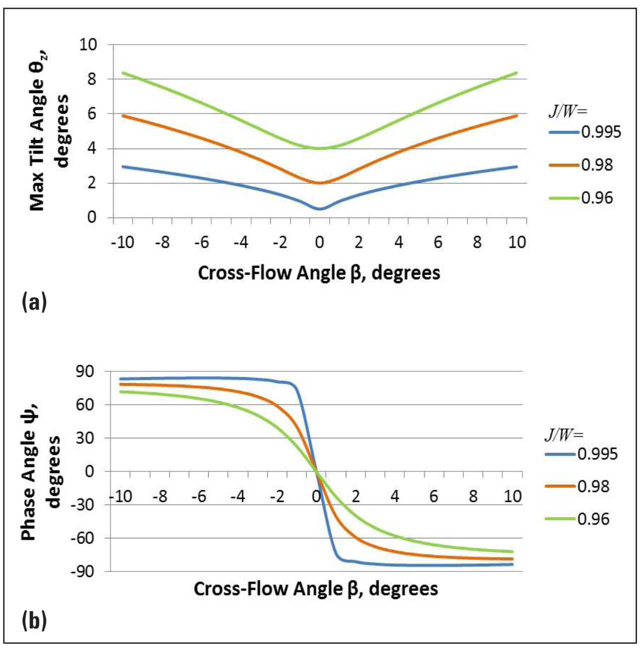
APPLICATION

Apart from influencing material removal during tape peels, the tilt angle is important because the z-depth of penetration of a tilted fiber segment may be sufficient to bond a number of fiber layers. Suppose a paper consists of layers that are roughly τ thick. A fiber segment of length Λ is tilted at an angle Θ_z. The number of layers penetrated and potentially bonded by the fiber is the integer value of

$$N(\theta) = \sin(\Theta_z)\Lambda/\tau = \cos(\psi-\theta)\sin(\theta_z)\Lambda/\tau \quad (5)$$

Since any two adjacent layers have bonding potential independent of fiber tilt, N must be at least 3 to make a distinct contribution. By this standard, $\Lambda = 200\mu m$, $\tau = 5\mu m$ and $\Theta_z \geq 4.3°$ describe conditions for which z-direction bonding from tilted fibers can be important. From Eq. (3), assuming a jet-to-wire velocity differential of 2%, a cross flow of $5°$ and $n = 2$, the calibration constant T must be at least 1°/% to achieve $N = 3$.

The values $n=2$ and $T=1°/\%$ are used in **Fig. 3a**, showing the variation of peak tilt angle as a function of β for different values of J/W ratio. The nonlinear dependencies of Eq. (3) are largely self-compensating, resulting in generally linear increase in peak tilt angle with cross-flow angle. Different J/W ratios provide an offset tilt angle that decreases as J/W approaches unity. The likelihood of sufficient tilt to bond multiple fiber layers increases with increasing cross-flow angle and increasing jet-wire differential.



3. (a) Maximum fiber tilt angle versus cross-flow misalignment angle and (b) in-plane orientation angle for maximum fiber tilt downward toward wire and reel.

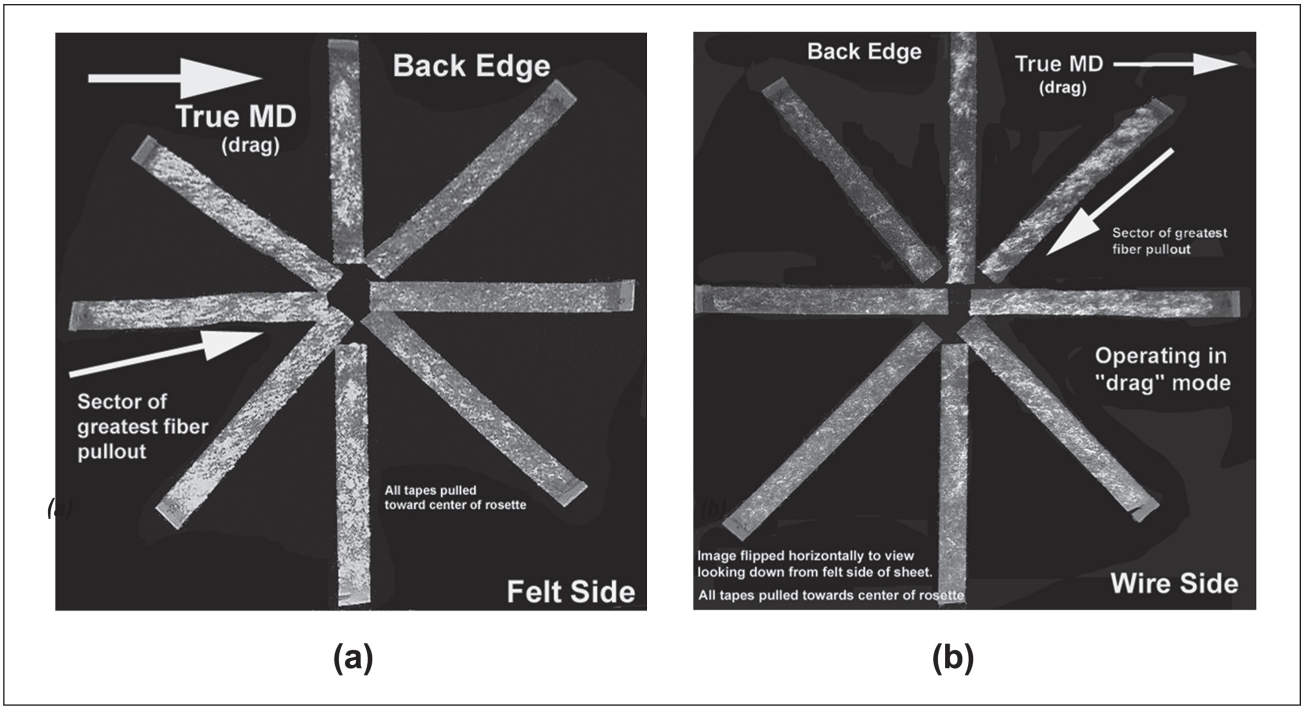
Figure 3b is a plot of the phase angle ψ over the same range of cross-flow angles and J/W ratios. At all ratios, there is an initial rapid change of phase angle with respect to cross-flow angle, followed by a saturation effect in which the phase angle is increasingly independent of cross-flow angles above ±4°. Phase angles near ±90° indicate that CD oriented fibers in the sheet are those experiencing the largest tilt. One implication is that improvement in out-of-plane shear strength accomplished by tilted fibers should be more pronounced in the CD than in the MD for sheets with significant fiber misalignment. This should be testable using, for example, the double-notch shear test [19]. Another implication is that fiber pullout should dominate for CD tape peels (at least in the appropriate CD direction) when there is significant fiber misalignment. In cases where fiber misalignment is minimized for good sheet performance, increases in both out-of-plane shear strength and fiber pullout favor the MD, though effects should be smaller.

In general, peel angles ψ resulting in largest fiber pullout are directly related to the cross-flow or fiber-misalignment angle β by means of Fig. 3b. In principle, measurements of ψ from tape peels can be used to predict β when J/W is known. Accuracy improves for smaller values of β where the slopes in Fig. 3b are largest. Except for differences owing to change in the sign of tilt, response to tape peels is very similar for rush or drag conditions having the same absolute value $|J/W\text{-}1|$.

TAPE-PEEL DEMONSTRATION

The present model applies Finger and Majewski's work [1] to cross-machine flows and offers a mathematical model connecting fiber tilt to forming and hydrodynamic parameters. It is instructive to see how the model may be applied to determine fiber misalignments using a tape-peel rosette taken from the literature [11]. This does not prove the model but gives an understanding of its potential, including the accuracy expected from a single test. It also describes an approach to measuring tape-peel rosettes based on image processing.

The key to extracting quantitative information about cross flows from tape-peel rosettes is to measure the amount of material peeled from the sheet at any given angle. Although tilted fibers may initiate pullout, there is likely to be a multiplier effect in which individual tilted fibers result in many nearby fibers, tilted or not, deposited on the tape. When deposited fibers become a significant fraction of all fibers in the paper, the more complicated is the connection to fiber tilt. This seems to apply to the heavily fibered Finger and Majewski rosette (Fig. 6 in [1]). A better situation is one in which relative-



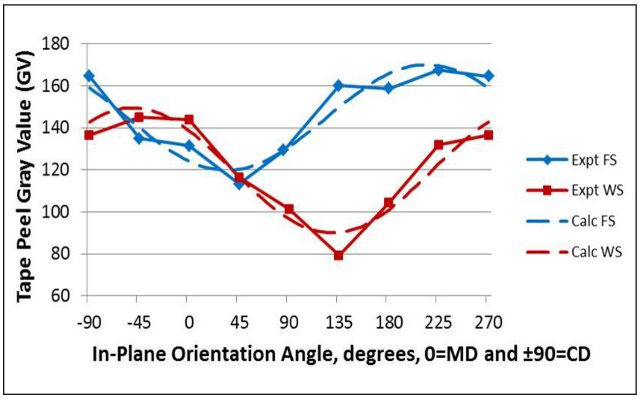
4. Tape-peel rosettes, after MacGregor [11], with all peels terminating at the center; (a) felt side and (b) wire side. Wire-side strips are positioned in angle as they would appear if they had been taken from just beneath the corresponding felt-side strip, so that high felt-side fiber pullout generally corresponded to low wire-side fiber pullout, and vice versa.

ly few fibers are peeled from the sheet. Even if the weight of peeled fibers is too low for gravimetric measurement, the tape strips can be imaged against a dark background. Image processing software can be used to assign an average gray value to the peeled fibers. In applying the present model, this gray value is taken to be representative of the underlying fiber tilt.

Figure 4 shows tape peels from a light-weight coated (LWC) base paper made under drag conditions on a Fourdrinier [11]. Tape peels were made at 45° intervals, labeled counter clockwise from the MD. Wire-side and felt-side results for the same angle were peeled parallel to each other, toward the center of the rosette. Gray values were quantified using Image Warp software (A&B Software; New London, CT, USA). Measured regions of interest were limited to each rectangular tape area and excluded the end gripped during the experiment. Dark regions correspond to less fiber pullout; white regions correspond to greater fiber pullout.

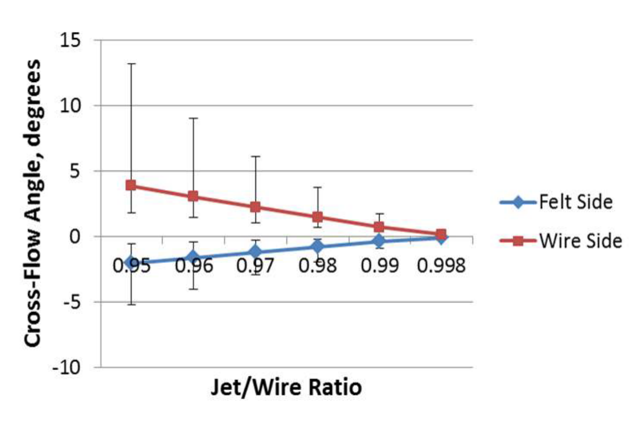
Variations within a single peel could indicate small-scale spatial variability in the cross-flow angle β. Previously, we indicated that β seen by an individual fiber was an average over the space and time required for its drainage. Now we add the need to average β for all fibers over the footprint of the rosette. The situation is similar to the averaging done to produce ultrasonic stiffness measurements over a circular footprint using radial measurements of acoustic velocity conducted at different angles [20].

Figure 5 shows experimental gray values (GV) and the best fitting sine curves according to a least-squares fit. Felt- and wire-side curves feature different degrees of phase shift relative to the MD. Assuming J/W=0.98, the gray-value minimum at 34° on the felt side corresponds to a cross flow angle of -0.8°. On the wire side, the gray value maximum at -51° implies a cross flow angle of +1.5°. The accuracy of these numbers depends on accuracy of the phase angle measurement as well the J/W ratio. Unfortunately, phase uncertainty is comparable to the 45° tape-peel measurement interval. For felt-side phase, the 95% confidence range extends from 10° to 58°, and the corresponding range in β is -0.2° to -1.9°. For the wire-side phase, the range is -31° to -71°, and the range in β is 0.7° to 3.8°.



5. Best-fitting sine waves to experimental gray-value data; FS=felt side and WS=wire side.

If the jet-to-wire ratio of the paper machine were not 0.98, as assumed, other choices for cross-flow angles give similar correlations. **Figure 6** shows the trend of cross-flow angles as the jet-to-wire ratio varies from 0.95 to 0.998. The result is



6. Variation of cross-flow angles with assumed jet-to-wire ratio. Plotted angles provides the best correlation with experimental gray values at the J/W ratio indicated. Error bars indicate 95% confidence limits of cross-flow angles as determined by phase variability in tape-peel gray values.

essentially linear, with the ratio of wire-side angle to felt-side angle always within 1% of 1.87. In other words, tape peels are really telling us the derivative $d\beta/d(J/W)$, and knowledge of *J/W* is needed to know the cross-flow angle. Error bars in Fig. 6 represent the 95% confidence interval for the cross-flow angles at each jet/wire ratio. These are associated with uncertainty in knowing the phase of tape-peel gray values when plotted against peel angles. The asymmetry of error bars is associated with the nonlinear response of the in-plane phase angle to the cross-flow angle β, as shown in Fig. 3b.

DISCUSSION

More than fifty years ago, Finger and Majewski characterized the relationship between fiber tilt and cross-machine flow variations on the Fourdrinier wire [1]. The present work is an attempt to formalize their discussion in a mathematical model, and to apply the model to tape peels, an easy way to demonstrate the presence of tilted fibers in paper.

A tape-peel rosette reveals a sine-wave pattern with the greatest amount of peeled material often shifted in angle relative to the machine direction [1,11]. The present model provides a way to interpret the phase shift in terms of cross-flows on the wire, or equivalently, fiber misalignment. Measurement noise results from phase uncertainty and often imprecise knowledge of jet-to-wire ratio. Nevertheless, the model helps to show why tape peel rosettes have been qualitatively useful for forming-zone optimization [11]. The model also introduces parameters for describing the peak tilt angle of fibers. It is complicated to predict how fiber tilt might influence tape peels in view of the many competing and extraneous influences contributing to fiber pullout. In the demonstration, however, it was interesting to note that peak-to-valley gray value differences were slightly greater on the wire side than the felt side, consistent with the larger magnitude cross-flow angle β found there and the larger fiber tilts associated with larger β, as shown in Fig. 3a.

The phase difference observed between the two sides of the sheet leads to an assignment of different cross-flow angles on the felt and wire sides. Optical reflection methods that measure frozen-in cross-flows in the form of fiber-orientation misalignments are also sensitive to two-sided differences [21,22]. This is in contrast to ultrasonic methods [20,23]. One of the optical methods has offered supporting evidence for felt-side and wire-side angle differences as large as 10° [24]. In view of this, the assignment of cross-flow angles of -0.8° on the felt-side and 1.5° on the wire side does not seem extreme. MacGregor shows a fiber-orientation angle profile of the web from which the tape-peels of Fig. 4 result [11]. The angle trends towards 0° near where the tape peels were made, consistent with our assignment of negative and positive cross-flow angles that nearly average to zero. Future work to refine the model should be done with careful attention to the rush-drag value of the process and the fiber misalignment angle(s) β as measured optically (on both sides) or ultrasonically.

Some noteworthy differences between the angle information provided by tape peels and by optical reflection measurements should be mentioned. Suppose, as in Fig. 6, that β is proportional to *J/W* over a range of interest. Optical-based fiber-orientation measurements would show this directly. Tape-peels, on the other hand, are sensitive to the slope $d\beta/d(J/W)$ and would remain constant as *J/W* is varied. The angle β would be determined by multiplication of the slope and the actual deviation of *J/W* from 1.0.

Another point of difference is illustrated in Fig. 3b. For small cross-flow angles, say from $0° \leq |\beta| \leq 2.5°$, the in-plane phase angles from tape peels vary approximately linearly with β and are very sensitive to it. From $2.5° \leq |\beta| \leq 10°$ these conditions cease to apply. This implies that phase variations in tape peels will be most accurate for measuring small cross-flow angles near β=0°, and less accurate for large cross-flow angles near β=10°. In contrast, the response of optical-reflection methods should be uniform over this range.

In most practical situations, response sensitivity in the range $2.5° \leq |\beta| \leq 10°$ is preferred for troubleshooting forming problems [15-17]. However, the sensitivity of tape peels to small angle variations near β = 0° could be useful in studying the short-term variability of well-controlled machines. Aidun has found that the interaction of secondary flows from adjacent tubes in a headbox tube bank produces streaks that survive impingement on the wire [25]. Before impingement, the streaks were observed to change in angle by about ±0.2° in 0.5 meter of travel. The angle could possibly be amplified by interaction with the wire. Though the resulting fiber misalignments may be too small to cause converting problems, they may produce fiber tilt of the type characterized by the present model. If long tapes are peeled adjacent to each other in the MD, variations in the amount of fiber pullout could be qualitatively revealing of small CD structure changes similar to those suggested by Aidun's high-speed videos [25].

CONCLUSIONS

Fiber tilt in papers depends in part on the jet-to-wire velocity differential during forming and the angle of cross flows commonly associated with fiber-orientation misalignment. A model for the interaction predicts a sinusoidal variation of fiber tilt angle with the in-plane orientation angle of the tilted fiber. The in-plane orientation angle associated with maximum tilt represents a large amplification of the cross-flow angle. By associating fiber tilt with degree of fiber pullout in tape peels, it is possible to use experimental tape-peel rosettes to measure small fiber misalignment angles. Tape peels may also be used to troubleshoot fiber-orientation converting problems when more conventional methods are not available [11]. In contrast to in-plane ultrasonic measurements, tape peels, like optical-reflection measurements, are sensitive to two-sided differences in fiber orientation [21,22,24].

Accuracy is limited by the angular resolution of tape peels, typically 45°, and by any uncertainty in the jet-to-wire ratio. Accuracy should be improved by averaging the results from multiple rosettes or decreasing the peel interval below 45°. Fiber misalignment angles measured by the technique likely represent averages over the footprint of the rosette.

Actual fiber tilt angles are not measureable with tape peels, nor are direct measurements of fiber tilt-angles currently possible by other means, except on a very small spatial scale [4,9,10]. Measurements of volumes roughly one million times larger than can be done at present are needed to characterize the practical importance of fiber tilt. Though limited in the information they provide, tape peel tests remain one of the best options for studying fiber tilt in large samples [1,11]. **TJ**

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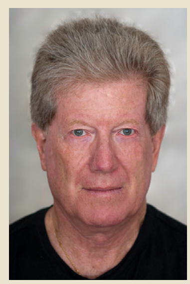
Vahey


Considine


MacGregor

We chose this topic to research because very little is known about fiber tilt and how it can be important to z-directional bonding of paper. Tape peels have been a fairly easy way to gain qualitative information about fiber tilt. We wanted to put together a model that would allow papermakers to extract quantitative information from tape peels as a start to understanding the impact of fiber tilt on paper performance.

In 1954, Finger and Majewski published an important paper in *TAPPI Journal* describing how cross-directional shake on a wire produced tilting fibers. We updated the work by applying it to cross-flows responsible for in-plane fiber misalignment. We devised a model for calculating the degree of tilt. The research also complements the work one of us (MacGregor) has done using tape peels to diagnose paper machine forming problems.

The most difficult aspect of this work was sorting out how fibers in cross-flows experience rush-drag differently, according to the in-plane direction in which they point. Rush-drag can cause one fiber to tilt down toward the wire side and reel, while a nearby fiber tilts up!

The moment of truth for any math-based model is comparing it with experiment. We were surprised at how well the model fit images of tape peels conducted years earlier in a situation where only qualitative interpretation was possible. Because tape peels are relatively quick and easy to perform, mills could benefit from establishing a library of tape peels to revisit during times of forming problems. Tape peels provide information about fiber misalignments and sheet two-sidedness that is complementary to that obtained from standardized optical and ultrasonic test instruments.

In the next step, it will be interesting to compare tape peels from a set of papers to related information from optical and ultrasonic orientation tests. It must also be noted that the value of tape peels as a quantitative tool depends on accurate knowledge of the rush-drag differential, which is still a challenge.

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