Simulation of creping pattern in tissue paper

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KEYWORDS: Simulation, Creping, Tissue paper, Welch spectrum, Image

SUMMARY: The key operation in tissue production is the creping at the Yankee cylinder. The tissue sheet is adhered to a Yankee cylinder and then detached from the surface with a blade. As a result a strong microstructure – crepe folds – is generated on the web. In this work the structure of creping pattern in CD and MD of tissue paper was studied. The samples available in this work consisted of bath tissue and towel grades. The significant difference between the samples was in the number of crepe folds. The tissue sheets were analyzed with an imaging system. The variation of crepe folds in images was studied in spatial frequency space through 2D Welch spectrum. It was noticed that the difference in creping pattern structure between the samples can be seen clearly in spectra. The creping pattern was simulated based on the creping pattern variation found from the Welch spectra of tissue paper images. The simulation was based on a set of sinusoidal terms representing several orientations and amplitudes. The amplitudes of sinusoidal terms located in regular grid in spectra were approximated with 2D normal distribution. Thus, the structure of creping pattern can be represented with three parameters originating from the deviations and location of 2D normal distribution. The creping pattern reconstructed with simulations contains the relevant features in the creping pattern of true tissue images.

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Tissue products have promising future markets due to their sustainable raw material and lack of competing materials. Therefore it is expected that tissue manufacturing will continue to increase, which increases the financial significance of understanding the phenomena in tissue making process.

The wet-end of tissue machine is quite similar to that of the printing paper machines. The most common type of tissue machine is the dry crepe machine in which the sheet is dried on only one drying cylinder. This is because the strength of the low basis weight sheet is not enough to support sheet transfer. Such cylinder is called the Yankee cylinder. The tissue sheet is adhered to the Yankee cylinder and then detached from the surface with a blade. As a result a strong microstructure – crepe folds – is generated on the web. The detaching, known as creping, generates high softness (Hollmark, Ampulski, 2004) and also stretches such that the sheet can be transformed from the Yankee cylinder to the reel without a web break. As a result also the basis weight of the sheet increases which is a consequence of creping and speed difference between the reel and the Yankee cylinder.

The creping mechanism is studied mainly in running direction of paper machine (Hollmark, 1972; McConnell, 2005; Ramasubramanian, 2011; Sun, 2000). Hollmark (1972) was the first who studied the creping mechanism from the experimental point of view by imaging the process with high speed cameras and by developing a description of the creping process. Ramasubramanian (2011), Sun (2000) and McConnell (2005) described mathematically the creping process. Contrary to the publications referred to above this paper studies and simulates the structure of creping in both cross direction (CD) and machine direction (MD) of tissue paper. This paper focuses on the scale of crepe folds whereas the detailed small scale structure of the crepe folds is ignored. It is known that the crepe folds are not regular oscillations in tissue paper. This is mostly because of the variation in adhesion between the paper sheet and the Yankee cylinder, and the small scale variation of basis weight and thickness in tissue paper (Archer, Furman, 2005).

In this work the variations are studied by computing the power spectra of images captured from tissue paper. The creping pattern is physically interpreted based on these variations. Furthermore, the structure of creping is intended to describe with only few parameters which represent the variation of creping pattern in CD and MD. Thus, the tissue grades can be classified easily based on these parameters and the connection between the interesting physical properties of tissue and the structure of creping can be studied.

The pronounced spatial frequencies in MD and CD directions present in creping pattern were studied from reflectance images of tissue paper. The variations were studied with the 2D Welch spectrum (Welch, 1967) estimation method.

The structure of this paper is as follows. The second section describes the material studied in this work. The third section introduces the creping mechanism and specifies the forces affecting in the creping process. The fourth section studies the variation in creping pattern and discusses the source of variation. In the fourth section the simulation method of creping pattern is presented. The section assesses the method by simulating the structures in bath tissue and towel samples. Section 5 concludes the results and discusses the validity of the evaluation and the usability of the results in controlling and developing the tissue making process.

Material

Material consists of two single ply tissue sheets manufactured in dry crepe machines in US. The grades represent two easily distinguishable tissue products: the at-home bath tissue product which has low wet strength and high softness, and the away-from-home towel product which has high wet strength and low softness. The basis weight of both samples was 20 g/m² and the
thickness of the bath tissue and the towel were respectively 0.065 mm and 0.05 mm. The tissue samples were cut on the top of a machine reel so the embossing, printing or other converting processes had not affected to structure of crepe folds in the samples.

The images of tissue samples were captured with a laboratory imaging device consisting of a digital system camera and LEDs. Fig. 1 shows two examples of these samples. Spatial variations of wavelengths higher than 3 mm were filtered out from the images as they were considered wrinkles rather than crepe structure.

It can be seen from the tissue images in Fig. 1 that the creping is not a perfectly controlled process which would produce identical crepe folds to a regular pattern. The crepe folds have variation both in CD and MD direction. Furthermore, the length of the crepe folds in CD is rather limited and varying from position to position and between samples.

The Creping Mechanism

The key phenomenon in tissue production in dry crepe machines is the creping mechanism. The sheet is pressed before the Yankee cylinder to remove water and to achieve a good thermal contact between the sheet and the Yankee cylinder. Next the sheet is adhered to a Yankee cylinder which dries the sheet completely by heating the water out of the paper. The dry sheet is scraped off from the cylinder with a blade. The scraping is called creping as it forms crepe folds in the sheet. Finally, the creped sheet is pulled to the machine reel. The lower speed in machine reel enables the creping without the brakes of the sheet. The speed ratio between the Yankee cylinder and the machine reel is called crepe ratio.

The Adhesion

The paper sheet is dry when it reaches the blade. The sheet and the Yankee cylinder must be adhered together to keep the sheet controlled till the blade creping. The adhesion is controlled with coating sprayed directly on the cylinder. The coating consists of several components i.e.; organic components, phosphates, modifiers, adhesive and release agents (Oliver, 1980). The phosphates and organic material reduce the blade wear, protect the surface of Yankee cylinder, and impacts on the adhesion in coating. The modifiers affect to the softness of coating. The duty of adhesive agents is to hold the sheet against the Yankee cylinder (Furman, Su, 1993; Nordman, Uggla, 1977). However, as a result of adhesive agents the crosslink between the sheet and the Yankee is so strong that the control of creping would be difficult without causing sheet holes and brakes. Therefore, the release agents are added to the coating to weaken the adhesion between the sheet and the Yankee cylinder and enabling smoothly controllable creping process (Furman, Su, 1993).

In this work the adhesion is considered as a single adhesion force resulting from the overall effect of the coating components, thus keeping the tissue sheet attached to Yankee cylinder. The sheet adhesion in turn impacts to the width of the crepe folds in MD. Low adhesion produces typically wide crepe folds and high adhesion narrow ones if the other factors in creping are kept constant (Stitt, 2007). Furthermore, the difference in thickness between the bath tissue and towel samples is a partly consequence of the difference in amount of crepe folds. Presumably, high adhesion in towel sample produce crepe folds which width in MD is small and therefore the thickness of tissue sheet is small. On contrast the low adhesion in creping of bath tissue sample generates wide crepe folds in MD and therefore also the thickness of sheet is high. However, the creping does not explain the thickness differences entirely as also the basis weight before the Yankee cylinder and the gap size between the blade and the Yankee cylinder impact on final tissue thickness.

The angle between the Yankee surface and the top surface of the blade

It is known that the angle between the top surface of the blade and the surface of Yankee cylinder determines the ratio of macro and micro folds in tissue paper (Oliver, 1980; Hollmark, 1972). The angle measured with respect to cylinder tangent can vary from 40 to 100 degrees being usually in the range 80-90 degrees (Oliver, 1980). At small angles the micro folds are piling up after creping thus forming a single macro fold (see Fig. 2, left). Such super creped tissue sheet are rather unusual and they may have creping ratio higher than 2. At large angles the macro folds are not necessarily formed or the size difference between the macro and micro folds is minor. As a result, in such tissue sheets the creping ratio is lower. The forming of micro folds at large angle is illustrated in Fig. 2, right. In this work the angle in both machines was 90 degrees and the creping ratios were 1.27. Therefore the differences in adhesion, in content of tissue pulp, and in basis weight and thickness (Archer, Furman, 2005) are the main reasons for difference of creping pattern in bath tissue and towel samples.

Fig 2. The impact of angle between the Yankee cylinder and top surface of the blade in creping. Left: The angle is small. Right: the angle is large. (Oliver, 1980; Hollmark, 1972).
The Propagation of Creping

The forming mechanism of crepe folds is the following (Ramasubramanian, 2011; Hollmark, 1972). The tissue sheet starts to buckle when the sheet hits the blade. The buckling is the consequence of the force which presses the sheet against the blade overcomes the adhesion which crosslink the sheet and the Yankee cylinder. The buckling continues until the sheet collapses completely and forms the crepe fold. At this point the formed crepe fold moves over because of the pulling force of the machine reel and as a result the adhered sheet behind the crepe fold moves towards blade. The adhered sheet starts to buckle and the entire cycle is repeated and as a result a creping pattern to the sheet is generated (see Fig. 3).

The adhesion, the angle between the surface of the blade and the Yankee cylinder, and the structure of the sheet (e.g. thickness, basis weight) determines the crack point (see Fig. 3, bottom right) in creping process. The crack point is rather same in CD and MD but it can vary slightly as a function of time and in CD when the adhesion and the structure of the sheet vary in MD and CD.

The basis weight, the creping ratio, and the angle between the Yankee cylinder and the top surface of the blade were identical for bath tissue and towel samples. However, the properties such as softness and wet strength differ between the samples. The differences are due to the adhesion difference and the other differences such as the properties of fibers and the moisture of the sheet in creping process. The differences of creping patterns between the samples are studied in next chapter to detect how the varying variables in tissue making process affect to structure of creping pattern.

Variation of creping pattern in tissue samples

The variation of the length and the width of the crepe folds and the distance of the crepe folds can be studied through wave numbers. Wave describes in this work the ratio of the wavelength of the crepe fold to the width of the crepe fold. The wave number of highest squared amplitude in MD direction describes the orientation of crepe folds width in MD. The width of the high intensity area in k_{MD} direction describes the variation of crepe fold width in MD. The width of the high intensity area in k_{CD} describes the orientation variation of crepe folds in tissue sheet.

In bath tissue (Fig. 4, top) most of the variation is between the wave numbers 1 and 5 1/mm in k_{MD} direction corresponding wavelengths 1 mm and 0.2 mm. The wave number of highest squared amplitude in MD was 2.6 1/mm corresponding to wavelength of 0.38 mm. On the contrary, the towel spectrum (Fig. 4, bottom) spreads widely to wave numbers between the 2 and 9 1/mm in k_{MD} direction corresponding wavelengths 0.5 mm and 0.11 mm. The maximum number of crepe folds in MD was 4.7 crepe folds per mm corresponding to wavelength of 0.21 mm. In the towel spectrum (Fig. 4, bottom) the high intensity area is wider in k_{CD} direction. However, the wide variation exist at large wave numbers in k_{MD} direction. Therefore, the variation in the orientation of crepe folds is rather similar in both the tissue grades as can be seen more clearly when the spectra are transformed into polar coordinates (see Fig. 5). In this representation wavenumbers are pairs of angle \( \phi \) and distance \( k \) from the origin.

The main difference between the samples was the variation in the number of crepe folds which is probably due to changes in adhesion between the sheet and the Yankee cylinder. The higher number of crepe folds in the towel can be seen clearly in the polar spectra as a more stretched high intensity area in the \( k \) compared to bath tissue grade. The squared amplitude of variation in
high intensity area in the towel spectrum is lower by a magnitude compared to that in bath tissue. Indeed, the total variation in towel image was roughly one third of that in bath tissue which is partly due to the height difference of crepe folds between the samples.

Representation of creping pattern

In this work the structure of creping was illustrated with a set of sinusoidal wave fronts. In ideal creping process the creping pattern would be regular wave front having no variation. Such creping pattern, assuming that the creping is a sinusoidal wave front, would produce infinitely narrow wave number peak pair to the power spectrum, and in the case of non-sinusoidal wave front contain harmonics of the peaks. However, the creping pattern is not regular but both the orientation and planar size of crepe folds vary. Such variations broaden the narrow spectral peaks of regular structure causing the wide high intensity area to power spectrum (see Fig. 4-5).

Simulation of creping pattern

Let \( x \) denote the point \((x_{MD},x_{CD})\) in 2D spatial space and \( k \) the point \((k_{MD},k_{CD})\) in 2D dimensional wave number space. The Fourier transform of \( f(x) \) written as \( F(k) \), describes the amplitude, orientation and phase of sinusoidal terms so that when summing the sinusoids reproduces \( f(x) \). In this work the creping pattern was simulated by set of sinusoidal wave fronts whose orientation and amplitude follow the simplified representation of the 2D Welch spectra of tissue images. The simulation in general is obtained as follows

\[
\text{CrepingPattern}(x, W, H, k_0) = \sum_{i=1}^{N} I(k_i, k_0, W, H) \sin(2\pi k_i x - \phi(i))
\]

where \( N \) is the number of sinusoidal terms chosen for simulating the creping pattern and \( \phi(i) \) is the phase function of the sinusoidal term. The phase function \( \phi(i) \) is chosen uniformly distributed in \([0, 360] \) as this is the only distribution leading to translational invariance i.e. the pattern will not depend on the choice of world coordinate origin. The \( k_i x \) can be denoted with polar coordinates as follows

\[
k_i x = k \cos \theta x_{MD} + k \sin \theta y_{CD}
\]

where \( k \) is the radial wavenumber of the sinusoidal term, \( \theta \) its orientation (Sonka et al. 1998). The distribution of the intensities of sinusoidal terms in simulated creping pattern is a 2D normal distribution approximating the high intensity area in Welch spectra in Cartesian coordinates. However, the intensity distribution can be approximated with other distributions as well. The intensity function is obtained as follows

\[
I(k_i, k_0, W, H) = \exp \left(-\frac{1}{2} (k_i - k_0)^T \Sigma^{-1} (k_i - k_0) \right), \text{where}
\]

\[
\Sigma = \begin{bmatrix} W^2 & 0 \\ 0 & H^2 \end{bmatrix}, \quad |k_{CD}| < 2H, \text{ and}
\]

\[
|k_{MD} - k_{MD0}| < 2W
\]

The standard deviations \( W \) and \( H \) determine the width of the intensity function in \( k_{CD} \) and \( k_{CD} \) directions in power spectrum. The \( W \) describes the width variation of crepe folds in MD and \( H \) describes the waviness and CD length of crepe folds. The orientation and the wave number of sinusoidal terms are adjusted such that they form a regular grid in wave number space. The regular grid simplifies generating of 2D intensity function. The center...
of the grid is \( k_0 \) denoted as \((k_{CD0}, k_{MD0})\) where \(k_{CD0}\) is zero and \(k_{MD0}\) is the average number of crepe folds in MD. The grid dimensions are four times \(W\) and \(H\). Finally, the sinusoidal terms described in the regular grid in the wave number space are weighted with the 2D normal distribution. The sinusoidal term in the middle of the grid has the highest amplitude. The regular grid visualized on the Welch spectrum of bath tissue and the normal distribution of intensity function are shown in Fig 6.

The simulation results are shown in Fig 7. The center point of sinusoidal terms which describes the average number of crepe folds in MD was \(k_{MD0}=4\) 1/mm. The standard deviation \(W\) and \(H\) were varied respectively between the 0.5-4 (1/mm) and between the 0.5-1.5 (1/mm).

It can be seen that simulated creping patterns vary significantly when the standard deviations in simulation are varied. The length of the crepe folds in CD is long when the \(H\) parameter is small (Fig. 6, top, left and right). On contrary, the length of the high amplitude crepe folds is smaller when the \(H\) parameter is large (Fig. 6, bottom, left and right). The large \(W\) (Fig. 6, top and bottom, right) disturbs the regularity in creping pattern. The simulation enables the creation of creping patterns with arbitrary parameters. Furthermore, the creping pattern in true tissue grades can be described with only three parameters; the standard deviations \(W\) and \(H\) and the average number of crepe fold \(k_{MD0}\).

**The assessment of simulation results**

The simulation parameters \(H\), \(W\) and \(k_{MD0}\) which describe the bath tissue and towel tissue grade most advantageously are searched. Pointwise linear correlation between the simulated image and the original tissue image is not a useful similarity measure because of the phase difference between the creping patterns. Therefore the assessment is based on the distribution of wave number. The approximate shape of creping pattern in wave number space described with 2D normal distribution is fitted to Welch spectrum of true tissue image. The fitting is done in Cartesian coordinate system. The fitting ignores the phase and thus the similarity of creping patterns is meaningful to study. The 2D normal distribution was compared to averaged Welch spectra (see Fig 4). Thus the general behavior of creping pattern was found.

The similarity of Welch spectra of simulated creping pattern and true tissue image was evaluated with Kullback-Leibler divergence which is nonlinear measure of the difference between the two probability distributions (Bishop, 2006). The range for divergence is from zero to infinity where zero is the divergence for same distributions. The equation of Kullback-Leibler divergence is shown in Eq 4:

\[
KL(P \parallel Q) = \sum P(i) \ln \frac{P(i)}{Q(i)}
\]

where \(P\) and \(Q\) are the probability distributions whose divergence is computed. The Welch spectrum is not a probability distribution but the spectrum values can be normalized in a way that the sum of the spectrum values is 1. Now the normalized spectrum describes the probability of each wave number.

The standard deviations \(W\) and \(H\) of the intensity function and the center point \(k_{MD0}\) of regular grid were optimized by minimizing the Kullback-Leibler divergence between the 2D normal distribution and Welch spectrum of original tissue images. The optimization problem is not linear and the optimization space contains several local optima because of finite number of sinusoidal terms. Therefore, the simulated annealing method is applied which should converge to global optimum (Kirkpatrick et al. 1983).

Fig. 7 shows the optimal 2D normal distribution and the reference Welch spectrum computed from the image of bath tissue sample.
known that the physical property of tissue such as softness is related to small scale creping structure and to creping pattern structure (Stitt, 2002). Thus, the correlation between the estimated parameters of creping pattern and physical properties of tissue paper can be studied.

The optimal parameters of the simulation were studied with Kullback-Leibler divergence. The method is developed for the estimation of divergence between the probability distributions which can evaluate only positive values (larger than zero). The Welch spectrum was converted to probability distribution by normalizing the variance to one. Kullback-Leibler distance between the spectra are studied and applied also in (Veldhuis, Kladders 2003; Georgiou Lindqvist, 2003). It is possible that the Welch spectrum evaluates zero values and in such location the divergence is not determined. However, the optimization was evaluated several times and the optimum was rather same in iterations which indicated that such disturbance is not relevant in this work.

The divergence was computed between the 2D normal distribution and the averaged Welch spectrum computed from the true tissue images. However, the phase information of creping pattern was ignored. Therefore, the divergence is not the absolute measure of the similarity between the creping patterns.

**Conclusion**

The creping is not a perfectly controlled process which would produce identical crepe folds to a regular pattern. The variations in creping structure are due to structure variation in tissue sheet and due to adhesion variations between the Yankee cylinder and the sheet. The main difference between the samples was the variation in the number of crepe folds which is probably due to difference in adhesion. The difference in number of crepe folds can be seen more clearly when the spectra are transformed into polar coordinates. Such representation also reveals that the waviness of crepe folds and the crepe length in CD is rather same in both grades however being bit higher in towel grade.

The structure of creping pattern was illustrated with a set of sinusoidal wave fronts. The distribution of intensities of sinusoidal terms was described with a 2D normal distribution which follows the shape of the high intensity area in Welch spectrum caused by the creping. Such approximation enables the characterization of the creping pattern with three parameters the first being the average number of crepes and the latter two describing the variability of the creping structure. Now, the structure of creping pattern can be representing compactly by three numbers and correlations between the physical properties of tissue and the structure of creping can be studied.

The assessment of simulation results is based on the similarity between the 2D normal distribution and the average Welch spectrum computed from tissue image. The similarity was computed with Kullback-Leibler divergence. The optimal parameters of simulation were searched and simulated creping pattern suggest that these three parameters adequately reproduce the features visible in original creping patterns.

**Discussion**

At present the structure of creping pattern is usually described with single parameter which tells the average number of crepe folds per unit length in MD (Archer et al. 2010, McConnell, 2004). However, in such method several characteristics of creping pattern are ignored.

We suggest that the creping pattern is better characterized by $k_{MD}$, $W$, and $H$, the first being the average number of crepes and the latter two describing the variability of the creping structure. The simulations suggest that these three parameters adequately reproduce the features visible in original creping patterns. Therefore, for example in mill studies on the effect process conditions, the creping pattern structure data can efficiently be summarized with the three parameters. This also serves as basis of understanding the differences in functional properties of the tissue, resulting from differences in the crepe structure. For instance, it is
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