DEVELOPMENTS IN ACTIVITY GENERATION ON FOURDRINIERS

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ABSTRACT

Activity generation and control are important parts of papermaking. Once the slurry leaves the headbox, floc size will grow rapidly if stock turbulence and activity are not maintained. Gravity foils and other standard wet end drainage devices are successful at activity generation, but at a cost. These devices use large negative pressure (vacuum) gradients to cause activity, which in turn cause lighter fibers and fillers to be drawn to the base of the sheet. This stratification effect on the slurry increases drainage resistance, requiring subsequent table elements to work harder to remove water. To prevent slurry stratification(a.k.a. sheet sealing) lower vacuum can be used, with consequent reduction in drainage. Activity will lessen, and floc size will begin to degrade sheet formation. Therefore, the papermaker is forced to balance the necessity for stock activity and dewatering with the need to prevent stratification. The ideal drainage device could independently control drainage and stock activity. With such a device sufficient activity would be generated, while water is removed in a manner that keeps vacuum levels low. One way to achieve this goal is to repeatedly remove and return a portion or all of the water into the slurry with an undulating drainage surface. This paper reports on the analysis of such a device. Classical fluid dynamic techniques were used to model the interaction between the drainage surface and the slurry. This solved system was then used as an input to an independent model, which predicted stock activity levels. Pilot trials were used to validate the fluid model. Significant agreement between the data measured during these trials and the predictions of the fluid model was found.

INTRODUCTION

Since before the Fourdrinier Brothers first made paper continuously over two hundred years ago, the fundamental objective of the wet ends of paper machines has been to create a homogeneous, powerfully bonded sheet from a suspension of cellulose fiber and other miscellaneous materials. To make this sheet, there are many natural effects to be overcome. When fibers are in suspension, they generally attract each other and form flocs. These flocs are detrimental to a sheet of paper because they are inherently non-homogeneous. Energy in flows approaching the slice can be controlled to reduce flocculation and cause uniform material distribution(1). Once the suspension leaves the headbox, controlling it becomes more difficult. Generally, papermakers induce turbulence into the open sheet to keep fibers evenly distributed and unagglomerated. When speeds were low, table rolls supported the forming wire and created alternating positive and negative pressure pulses that agitated the sheet, reducing floc size and draining the water. As machine speeds increased, the amplitude of table roll pulses became too large to be practical. Table rolls are still in use, but have been largely supplanted by foils. Hydrofoils were introduced to create more subtle positive and negative pressure pulses at higher speeds where table rolls proved impractical. Foils have proven effective over a very wide range of operation, but are not perfect devices. Activity and drainage in the forming section depend on a number of factors such as solids consistency, forming fabric characteristics, furnish characteristics, and a host of others. These things being equal, however, the single operational characteristic of a fourdrinier table that has the largest influence on that table's performance is the pressure amplitude and distribution applied to the fiber/water slurry. Positive and negative pressures create activity and cause most drainage. During its residence between the headbox and dry line, the sheet sees many quick pulses from foils, but is mostly at atmospheric pressure. Vacuum foils add a measure of control beyond this mostly "free" condition, but depend on vacuum to control drainage and activity. Higher activity levels are created by higher applied vacuum, causing the slurry and fabric to be deflected downward and the slurry to be churned from these Z-direction deflections. More vacuum causes more activity. Unfortunately, too much vacuum causes high rates of drainage, and the slurry becomes highly stratified and resistant to further drainage. A number of attempts have been made to extend the control of pressure over a wider range (References 2 and 3). None have proven commercially successful, but pose an interesting question: why is pressure applied in short pulses, and not in more consistent and controlled fashion?

The work presented in this paper explores alternate means of pressure application to the slurry, with the objective of control and optimization beyond conventional techniques. A theoretical model has been developed and will be described, as will its verification.

DISCUSSION

Objective

If the short, alternating positive and negative pulses of foils and the positive pulse/static vacuum of vacuum foils does not offer sufficient control of Fourdrinier operations to afford optimization, another method must be sought. A more controlled means of pressure application to create activity and drainage would be not impulsive but sinusoidal, or at least varying in a more wave-like fashion in the machine direction. Pressures could thus be sustained for longer duration and activity could be optimized without blowing apart the sheet. Also, drainage could be optimized and controlled to avoid sheet sealing. De-coupling of drainage and activity is also desirable, so each can be optimized.

The water/fiber suspension in the early part of a Fourdrinier can withstand positive pressures to only a limit dependent on its unit weight and surface tensions holding it together and on the fabric. Surface tension failures of water under conditions typically found in these systems seldom exceed four inches of water column. Thus, there is an inherent limit to the positive pressure that a given sheet can withstand.

Vacuum limits cannot be so easily understood. It is well known that early high vacuum levels are very detrimental to good operation and sheet quality. Retention is adversely affected because bottom fines and fillers are washed out. At the same time, the lower part of the sheet solidifies so that water above it is very difficult to drain. It is perhaps not, therefore, the vacuum itself which is detrimental, but the uneven Z-direction drainage caused by it. It would be advantageous to drain the sheet quickly if Z-direction solids content were consistent, and retention was not hurt. A pumping action on the sheet would be beneficial because Z-direction flows would homogenize the slurry and reduce drainage resistance.

What is required, then, is a foil that can generate wave-like pressure profiles so that activity is generated, sheet sealing is prevented, and drainage is enhanced. Because the sheet’s tolerance for positive pressure is so low, the key is to impart upward pressures in the sheet in a fashion that does not destroy the sheet. A long undulating foil can be used. Such foils have been applied (Ref 4), however their design is critical for the specific application to be successful. The design is accomplished through use of a fluid dynamic model.

Choosing a Model for an Undulating Foil

The first attempt to model this problem was performed by Walowit[5]. The author chose to view the problem as a modified version of Couette flow. The analysis accounts for the shear stress generated by the forming fabric and channel surface. The moving surface is treated as a porous media, and accounts for the flow restriction through the forming fabric. The control volume for this analysis can be seen in **Figure 1**. Initial experimental results were inconclusive, so a similar analysis, ignoring the shear stresses, was performed. The local channel surface pressure was estimated as the static pressure required to draw the necessary water needed to fill the void between the forming fabric and the channel surface. Once again experimental data was recorded and the results did not agree with the theory. After further analysis, it was evident that there were two major errors in the formulation. First, the assumption was made, in the formulation for the velocity profile, that the magnitude of the fluid velocity in the z-direction could be ignored, and that only the velocity component in the x-direction needed to be considered. The other problem arose in the narrow evaluation of the flow between the forming fabric and channel surface only. Experimental data showed that there were large pressure gradients where the forming fabric was in contact with the undulating surface, which made apparent that the fluid flow on top of the wire was just as important as the fluid flow underneath the wire. To broaden the domain of the analysis, we needed to concentrate more on the entire fluid motion, and less on the contribution of the forming fabric. To do this, it was apparent that open-channel theory was an ideal model for analyzing the flow over an undulating channel surface.

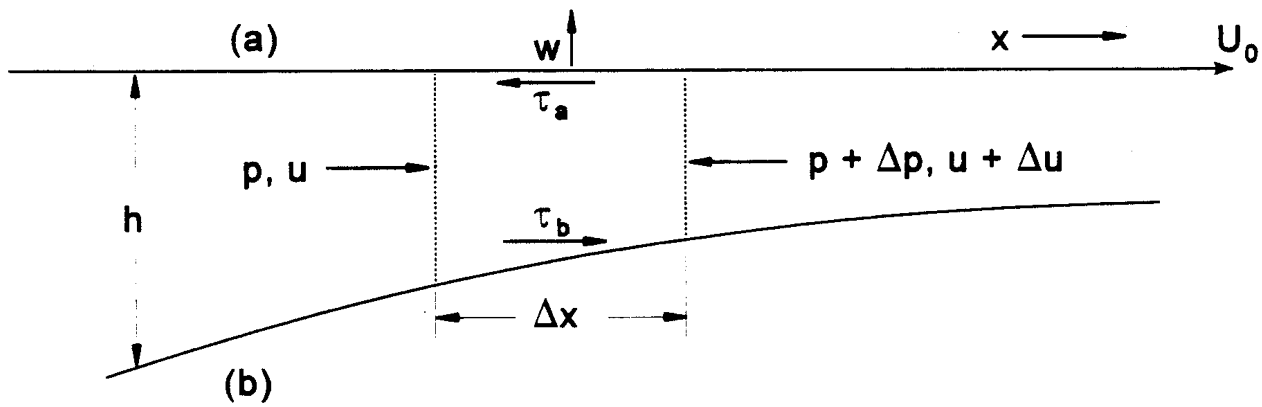

Figure 1. Walowit's Control Volume For Undulating Foil.

The Open-Channel Model for an Undulating Foil

The primary goal is to develop a model that will predict the amount of stock activity that a particular drainage device generates within the slurry. Traditionally this is measured by a visual observation of the Fourdrinier. At first glance it is apparent that stock activity is formed by changes in z-direction fluid velocity. To be able to predict stock activity, we must first be able to predict the velocity profile of the slurry as it flows over the drainage device. To pick an appropriate model, lets first isolate the undulated blade from the rest of the fourdrinier, as shown in **Figure 2**. This region contains the section of the drainage device that is in contact with the forming fabric, the forming fabric travelling at Uo, and the slurry entering and leaving this region with constant flow rate Q. This type of configuration, without the forming fabric, can be categorized as "open-channel flow". Essentially, we have a contoured channel bed that is transporting a layer of water from left to right. For now, we will ignore the forming fabric. Pressure profiles can be calculated using Reynolds' transport theorem for a control volume. It is important to calculate the pressure profile, because it is easier to measure pressure distributions, in a controlled experiment, than it is to measure a velocity distribution.

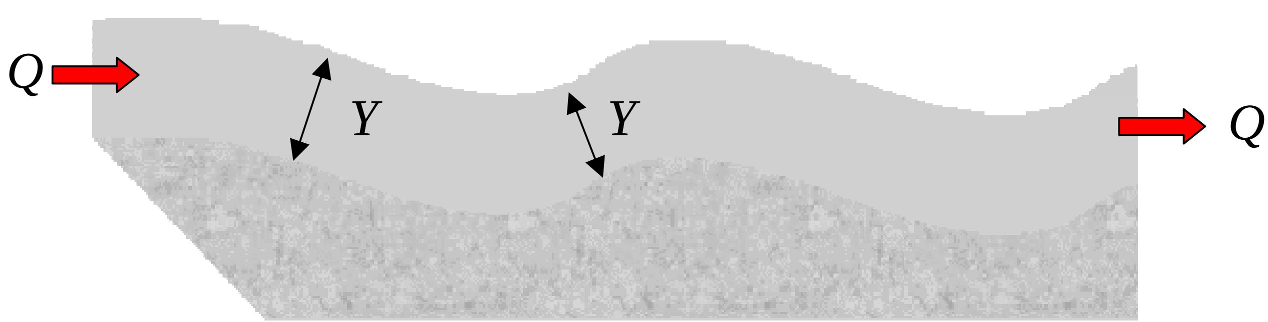

Figure 2. Domain of Open - Channel Flow Model for an Undulating Foil.

Velocity Profile Calculation

Considerable work has been done in the area of open-channel flow; therefore a detailed derivation of the applicable equations will not be done. As explained by Fox[(6)] and Chow[(7)] open-channel flow describes liquid flow through a channel with a free surface. The following is a list of important variables in open-channel flow:

U = mean velocity parallel to the local machine direction channel slope
Y = Local depth of the slurry normal to local channel surface (also cross sectional area per unit width)
H = distance from the forming fabric to the local channel surface
c = Celerity, or wave speed:

$$c = \sqrt{gY}$$

Fr = Froude number:

$$F_r = \frac{U}{c}$$

Q = Volumetric flowrate per unit width :

$$Q = UY$$

Sb = Bed slope:

$$Sb = \frac{dH}{dX}$$

S = Slope of the Energy Grade Line (Always >= 0)

In this case we have a steady system with constant in flow and out flow. To determine the machine direction velocity profile we must first define the shape of the free surface. Since there is a constant flow rate through the region defined in Figure 2, the local mean velocity is directly related to the local depth of the fluid:

$$U = \frac{Q}{Y}$$ **Equation (1)**

The following equation[6] defines the shape of the free surface:

$$\frac{dY}{dX} = \frac{Sb - S}{(1 - Fr^2)}$$ **Equation (2)**

This equation tells us that the change in the depth of the slurry is a function of the Froude number and the difference between the bed slope, which encourages flow acceleration, and the slope of the energy grade line, which retards flow acceleration.

The slope of the Energy grade line represents the head loss due to frictional effects with the channel bed surface and is estimated with the following equation[6]:

$$S = \frac{U^2}{Y^{4/3}}\left(\frac{n}{1.49}\right)^2$$ **Equation (3)**

Equations (1) and (2) define the machine direction velocity distribution and the shape of the free surface. There are, however, specific assumptions to these equations:

1) Inviscid flow

2) Small values for the bed slope, such that : $\frac{dH}{dX} = Tan(\theta) \approx \theta$

As described by Schlichting[8], and re-iterated by Chow[7], the water can be treated as inviscid outside any boundary layer that may develop over the channel surface. This makes boundary layer control an essential part of channel surface design. If changes in the bed slope are too drastic, boundary layer separation will occur, and the calculations will be wrong. The source of the error is that the flow will follow a different contour than that of the channel surface. The generation of a re-circulation zone (**Figure 3**) displaces the flow, including the free surface. To accurately determine the free surface shape and the effective depth of the slurry, equations (1) and (2) would be used based on the shape of the displaced flow as shown in **Figure 4**.

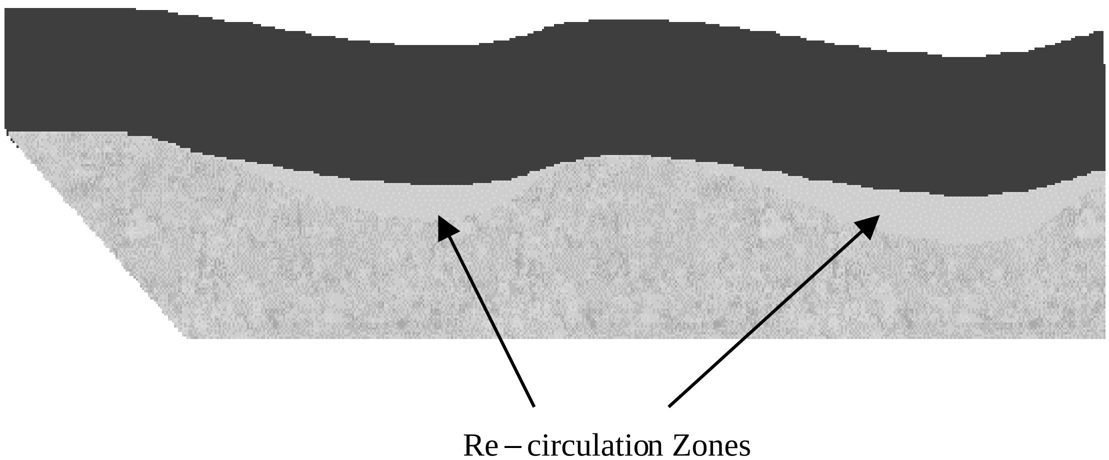

Figure 3. Development of Re-circulation Zones on an Undulating Foil.

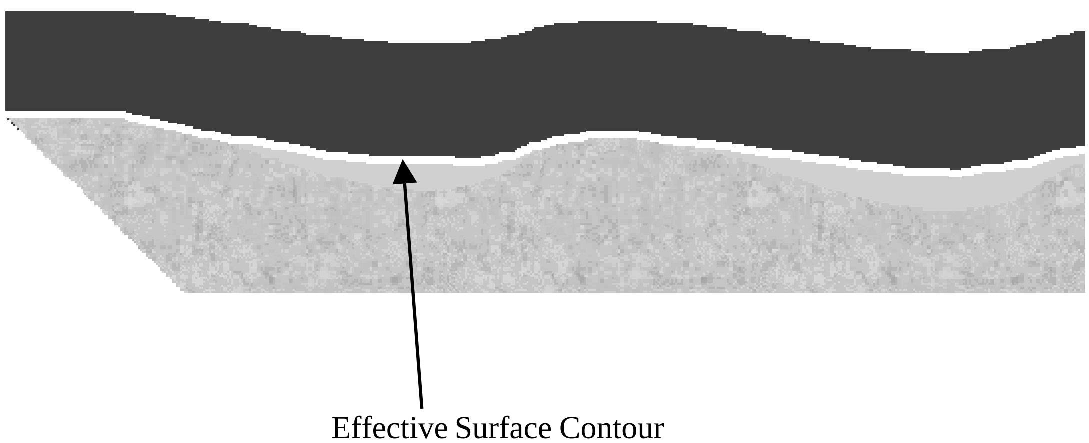

Figure 4. Displaced Slurry Path.

Pressure Profile Calculation

The next step is to determine an appropriate equation for the machine direction pressure profile. This is accomplished using a form of Reynolds transport theorem[9].

$$\vec{F} = \rho Q\left[U(\cos(\phi)-1)\vec{e}_t + U\sin(\phi)\vec{e}_n\right] \qquad \textbf{Equation (4)}$$

Equation 4 tells us, that the local pressure anywhere on the channel surface is that which is required to change the direction of the flow such that it follows the contour of the channel surface. Solving equation (4) for the control volume shown in **Figure 5** yields:

$$P(x) = \frac{\rho}{l}U^2 Y \sin(\phi) \qquad \textbf{Equation (5)}$$

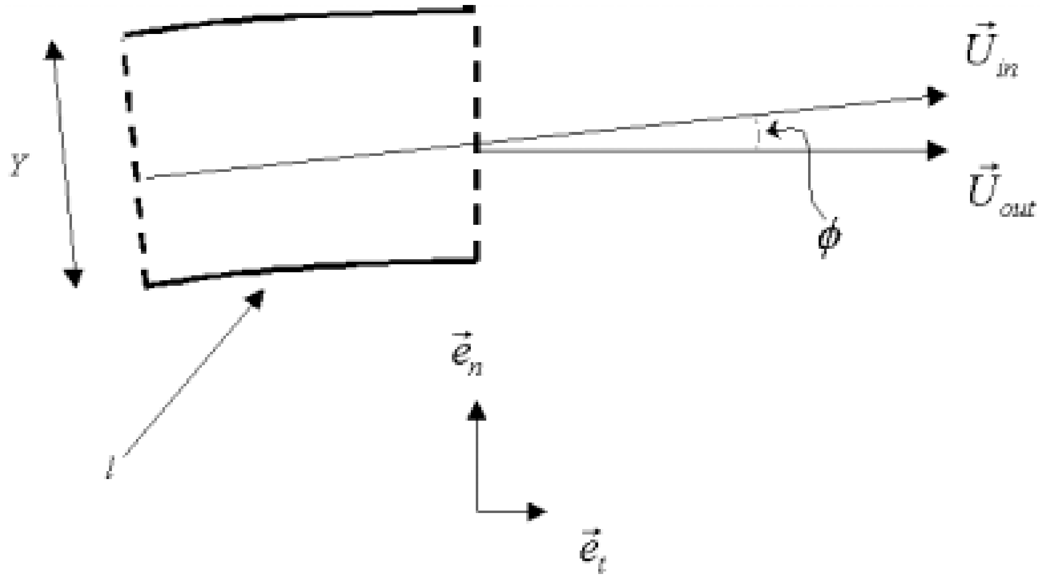

Figure 5. Force Balance Control Volume.

The sign of ϕ as shown in Figure 5 is considered negative. Equation (5) represents the pressure profile generated by the channel-flow equations. Two more terms are added to account for the effect of gravity and the flow restriction through the forming fabric:

$$P_{gravity} = \rho g \frac{Y}{\cos(\theta)}$$ **Equation (6)**

$$P_{fabric} = fU^2$$ **Equation (7)**

Where "f' is the forming fabric friction factor. Typical values for "f" can be found in **Figure 6**. Now we combine equations 5, 6 and 7 to obtain:

$$P(x) = \frac{\rho}{l} U^2 Y \sin(\phi) + \rho g \frac{Y}{\cos(\theta)} + fU^2$$ **Equation (8)**

Fabric	Friction Factor	Air Perm (cfm)
47 Mesh LDDL	25.3	n/p
54 Mesh Single Layer	27.5	640
54 Mesh 5/10 shed LDDL	45.5	480
95 Mesh 8 shed Duotex	46	450

Figure 6. Forming Fabric Friction Factors.

Figure 7 shows a plot of the pressure distribution predicted by equations 1,2 and 8. Notice the regions of the peak vacuum and peek pressure values. The sharp peaks are a direct result of abrupt changes in the slope of the blade surface, as defined by the mathematical algorithm. A machined blade profile would not have these abrupt surface changes, therefore experimental pressure measurements in these regions would show more rounded pressure/vacuum peaks.

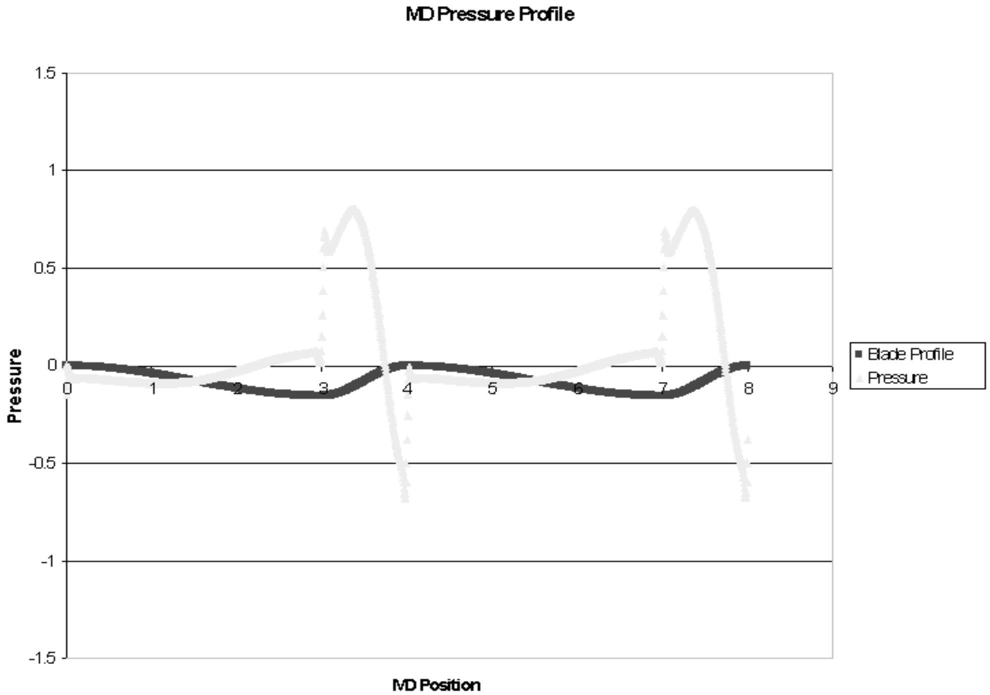

Figure 7. Theoretical Pressure Profile.

Figure 8 shows a picture of an undulated blade fitted with pressure taps. Pressure measurements were recorded for several conditions. **Figure 9-11** show the comparison between the experimental measurements and theoretical predictions. It is evident, from the decrease in measured pressure, that a re-circulation region has developed in the valley of the undulated blade. As the speed is increased, from 244 m/min – 488 m/min, the point where the experimental data starts to disagree with experiment move further down the MD direction of the foil. The point where theory and experiment differ is where the boundary-layer separates and the re-circulation region starts. As the slurry speed is increased, the re-circulation region gets smaller. This is because the added momentum, by increasing the speed, enables the flow to overcome the positive pressure gradients for a longer distance.

Figure 8. Undulating Foil With Pressure Taps.

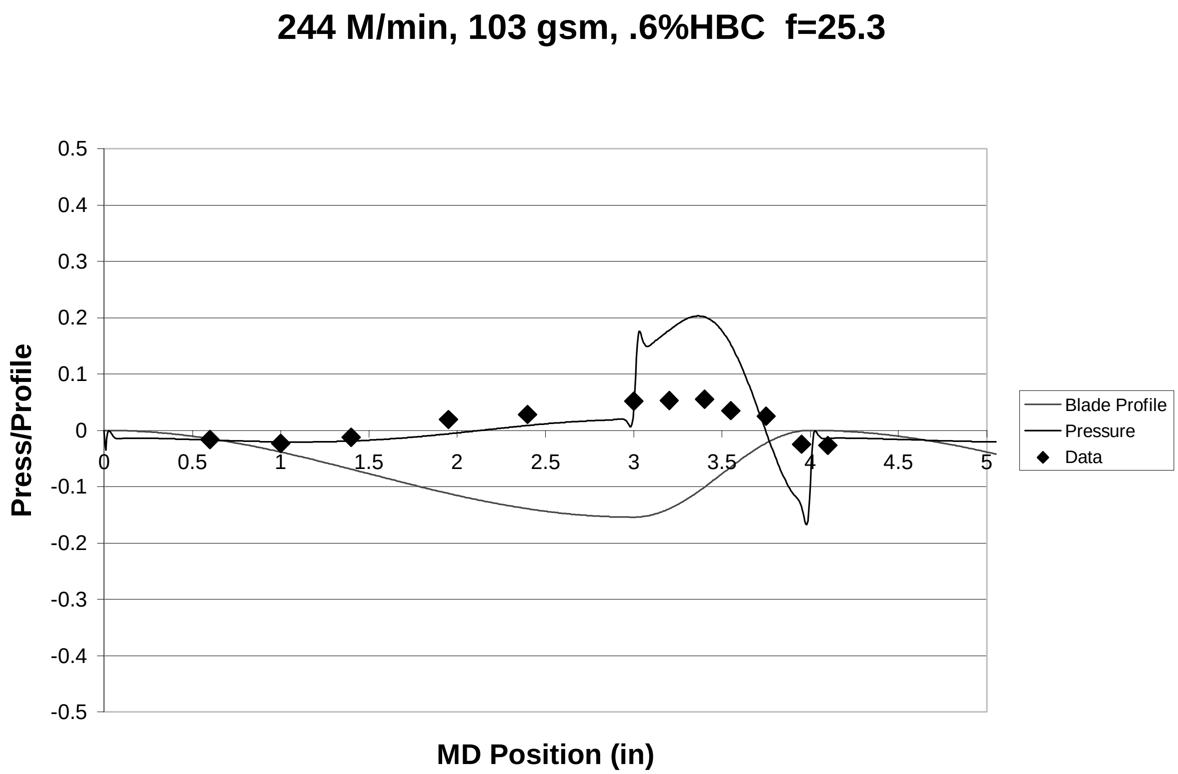

Figure 9. **Experimental Pressure Profile.**

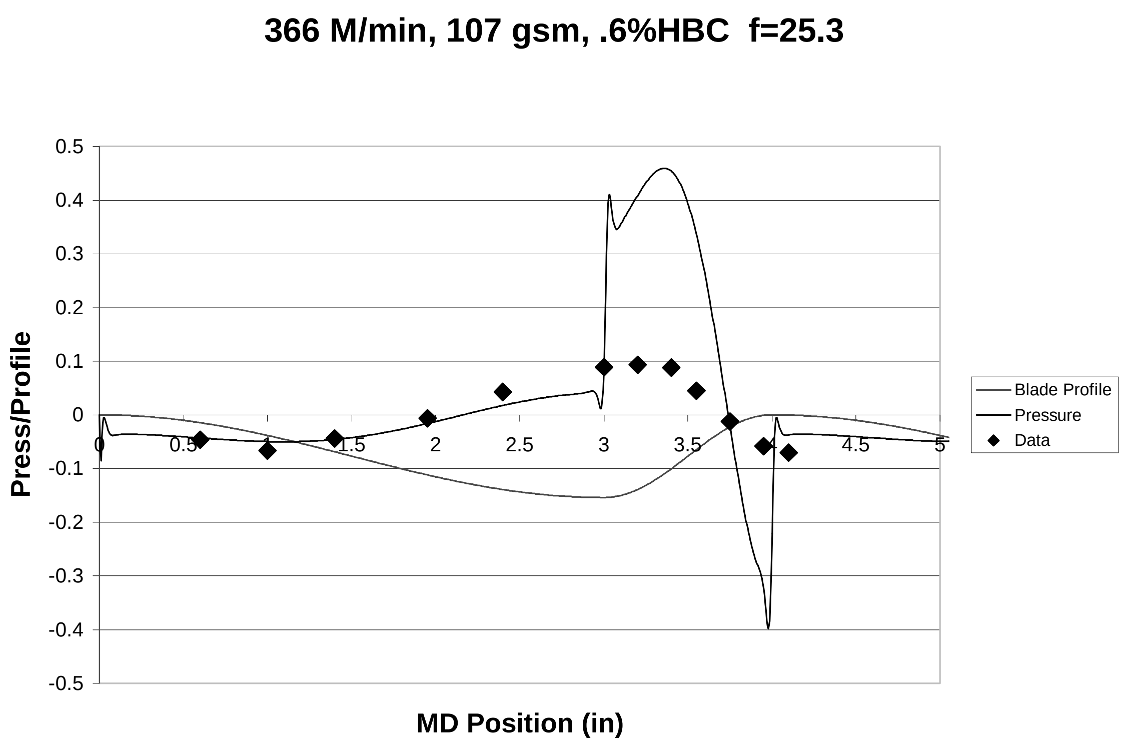

Figure 10. **Experimental Pressure Profile.**

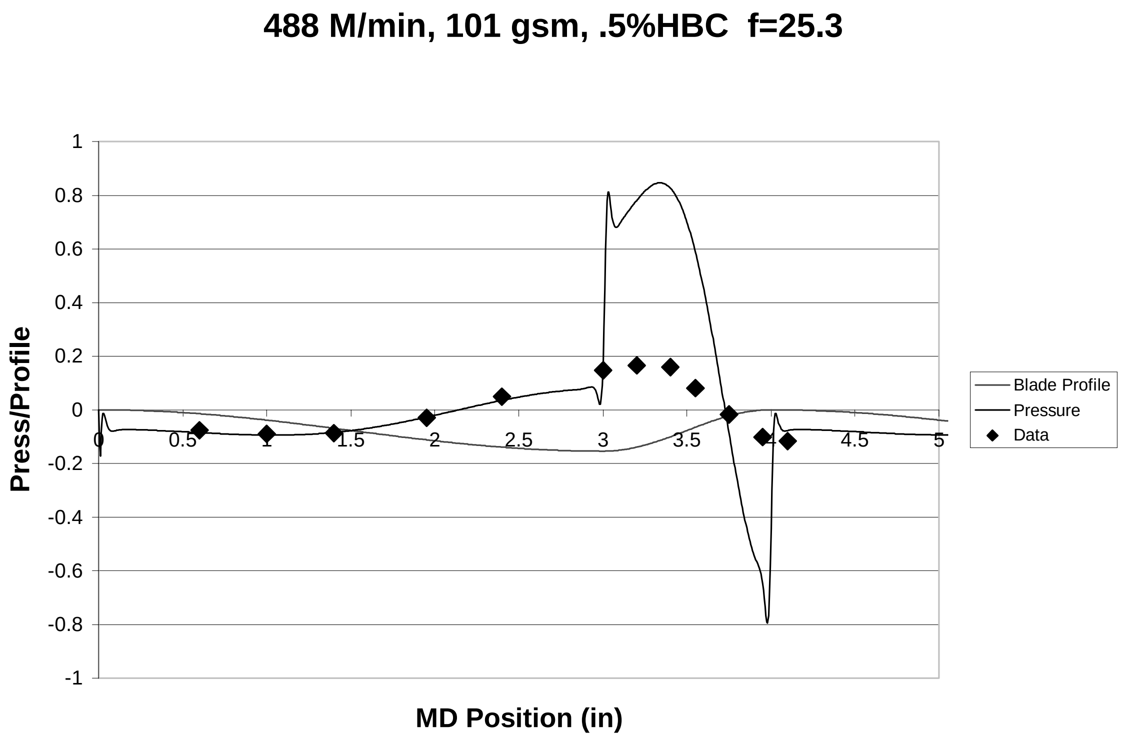

Figure 11. Experimental Pressure Profile.

Activity prediction

Several authors have written papers on the subject of stock activity, also know as surface instability. Yih and Lin[10] investigated the development of stock activity after a table roll. Results of their experiments showed a direct relationship between acceleration changes of the slurry and the amount of free surface instability. Mardon et al.[11] analyze the Fourdrinier from breast roll to flat box, showing how changes in acceleration generate surface wave instability. Another source of free surface instability is the waves generated by the interaction of the air/water interface. The faster the slurry is moving the, the stronger these effects are. Any "exact" prediction of stock activity would have to take into account the effects of each component of the fourdrinier as well as the air/water interface. However, to simplify things we will just focus on the undulating foil surface while retaining the knowledge of other surface wave contributors in the final result.

The pressure profiles calculated by equation (8) are in fact algebraic functions of the local fluid accelerations. Since an undulated blade generates a peak vacuum which is the same order of magnitude as the peak pressure, this peak pressure is directly proportional to the changes in acceleration the slurry goes through as it passes over the surface peaks. Therefore the peak pressure should have a proportional relationship to stock activity. **Figure 12** shows a plot of peak pressure values, measured on an undulating surface, versus stock activity levels. All of the data displayed was recorded for undulated foil blades mounted with a zero incidence angle with the forming fabric. Mounting the foil with a zero incidence angle creates a zero "net" vacuum over the entire foil surface, because of the cyclical nature of the foil shape. This lack of vacuum prevents a dense fiber mat from building up on the forming fabric since the cyclical nature of the vacuum/pressure pulses promotes slurry homogeneity. This zero "net" vacuum also limits the amount of drainage, although it can not be eliminated. Just like a forming board's open area can induce drainage, dependent on the open area, so would a group of undulated foil blades. If more drainage is preferred, the incidence angle of the foil blade could be increased until the desired amount of drainage is achieved.

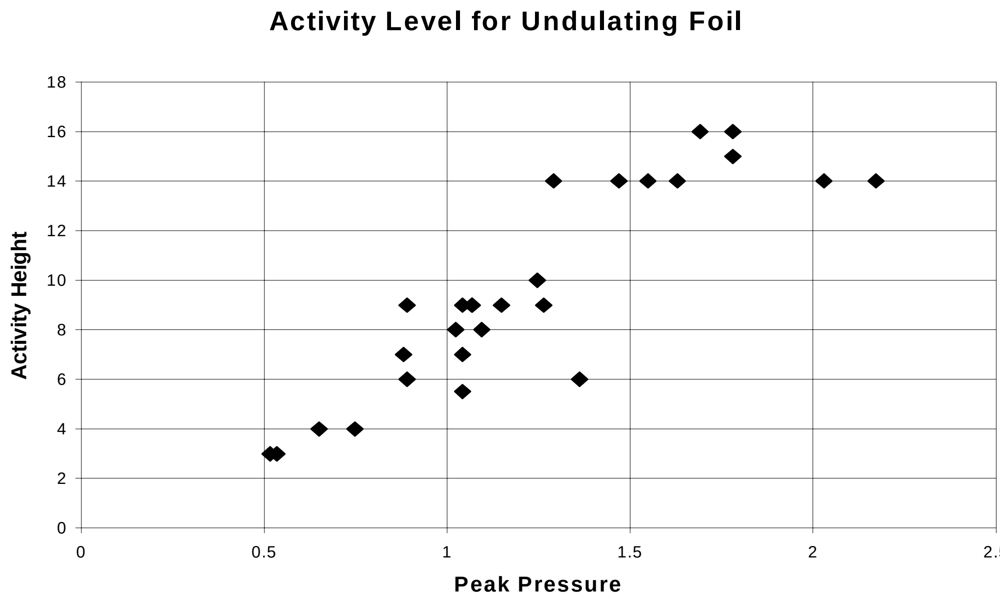

Figure 12. Activity Levels For Undulating Foil.

CONCLUSIONS

An undulating foil blade can be used to successfully generate stock activity independently from drainage. Open-channel flow theory can be successfully used to predict the pressure profiles produced by an undulating foil blade. It has been shown that surface instability is directly proportional to the peak pressure on an undulated foil. Therefore stock activity levels can be predicted provided that the foil design discourages the development of re-circulation regions, or the size of these regions can be estimated. While the forming fabric does contribute to the foil surface pressure profile, the most significant part is caused from the shape of the foil surface.

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