## ABSTRACT

*Pressure pulses between forming fabrics in twin-wire blade formers affect paper formation. These pulses have been modeled using four rigorously derived equations (mass conservation, momentum, top-fabric equilibrium, and bottom-fabric equilibrium) that describe the behavior of the fiber suspension and fabrics in a gap former. Results of this numerical analysis—particularly the pressure pulse generated by a forming blade—were compared with the approximate analytical solution derived by Zhao and Kerekes in a previous work (hereinafter, ZK). While most of the assumptions of that ZK model produced minimal errors, two produced consequential errors: The assumed constant permeability of the wire and associated fiber mat caused the peak pressure to be underestimated by about 15%. Moreover, the assumption that the stagnation point associated with the doctoring effect of the blades is negligible caused the ZK model to underpredict peak pressure upstream of the blade by 5–25%. For certain paper-machine operating conditions, the ZK model predicts the existence of an oscillatory pressure distribution upstream of the blade. The computational model presented here supports this prediction and shows that tension in the upper and lower fabrics plays a role in the development of the oscillatory pressures.*

***Application:***

*Presents a new computer model of the blade forming process as a first step in the design of better blade gap formers.*

# Numerical analysis of pressure pulses induced by blades in gap formers

SHELDON I. GREEN AND RICHARD J. KEREKES

In twin-wire blade forming, a pulp suspension is trapped between two fabrics under tension. The two fabrics are conveyed at high velocity (typically 15 m/s or more) and wrap around fixed blades. In the process, significant pressure pulses *(1–4)* are formed between the fabrics, which cause both rapid dewatering to occur and disruption of fiber flocs in the suspension, the latter of which improves formation. The rapid dewatering also has the negative side effect of producing poor retention.

Recently, Zhao and Kerekes *(5)* and Zahrai and Bark *(6)* have conducted theoretical analyses of pressure-pulse formation in a twin-wire blade former using, respectively, a one-dimensional linearized model and a two-dimensional potential-flow model. The objective here is to extend this previous work by including other effects—notably (a) the variable permeability of the wire and mat near a blade and (b) a doctoring pressure from the blade—that have not previously been modeled.

## THE COMPUTATIONAL MODEL WITH GOVERNING EQUATIONS

Four equations govern the behavior of a blade former. Those four equations are an equilibrium equation for the bottom wire, an equilibrium equation for the top wire, the continuity equation for the fluid filling the gap, and the momentum equation for the same fluid:

$$[EI_1(d^4y_1)/dx^4] - [T_1(d^2y_1)/dx^2] + [M_1V_0^2(d^2y_1)/dx^2] - p_B(x) + p = 0 \quad (1)$$

$$[EI_2(d^4y_2)/dx^4] - [T_2(d^2y_2)/dx^2] + [M_2V_0^2(d^2y_2)/dx^2] - p = 0 \quad (2)$$

$$V_F[(dy_2/dx)-(dy_1/dx)]+[(y_2-y_1)(dV_F/dx)] + k_2[2p - p_B(x)] = 0 \quad (3)$$

$$(dp/dx) + [\rho V_F(dV_F/dx)] + \left(\{\rho k_2[2p - p_B(x)]/(y_2 - y_1)\}(V_0 - V_F)\right) + [2\tau_w/(y_2-y_1)] = 0 \quad (4)$$

Equations 1–4 determine the following four unknowns:

1. The vertical displacement of the top wire ($y_2$) as a function of distance along the wire ($x$)
2. The vertical displacement of the bottom wire ($y_1$) as a function of distance along the wire
3. The pressure in the fluid between the wires ($p$) as a function of distance along the wire
4. The average fluid velocity between the wires ($V_F$) as a function of distance along the wire

**Figure 1** is a simplified model of a single blade of a gap former showing the model's important physical variables. The constants and fixed variables in Eqs. 1–4 are:

- $EI_1$ = bending stiffness of the bottom wire ($EI$ represents the product of elastic modulus $E$ and moment of inertia $I$)
- $EI_2$ = bending stiffness of the top wire
- $T_1$ = tension per unit length in the bottom wire
- $T_2$ = tension per unit length in the top wire
- $M_1$ = mass per unit area of the bottom wire with its adhering water layer
- $M_2$ = mass per unit area of the top wire with its adhering water layer
- $V_0$ = wire speed
- $p_B(x)$ = pressure underneath the bottom wire caused by the doctoring action of the blade on water adhering to the wire

$\rho$ = fluid density

$k_2$ = permeability of the wire with its associated fiber mat. (As discussed later, $k_2$ can be a function of $x$.)

$\tau_w$ = viscous shear stress exerted by the wire on the fluid between the wires. If the flow in the gap is assumed to be Newtonian, laminar, and fully developed at the local (assumed constant) gap size $H(x) = y_2(x) - y_1(x)$, then $\tau_w = 6\mu [V_F(x) - V_0]/H(x)$.

The permeability of the wire and associated fiber mat will normally decrease with $x$ because of the buildup of fibers on the wire. If $k_2$ is a function of $x$, we need an additional equation to describe the variation of $k_2$. If the fiber mat behaves like a porous medium obeying Darcy's Law, the drainage resistance of the wire and the fiber mat should be linearly related to the thickness of the fiber mat:

$$\text{drainage resistance} = C_1 + C_2 X(\text{mat thickness})$$

If the concentration of fibers in the fluid layer between the wires (i.e., not counting the fibers adhering to the wires) is approximately constant, then the thickness of the fiber mat is directly proportional to the amount of water pressed out from between the wires:

$$\text{mat thickness} = C_3\{[y_2 - y_1]_{\text{ref}} - [y_2 - y_1](x)\}$$

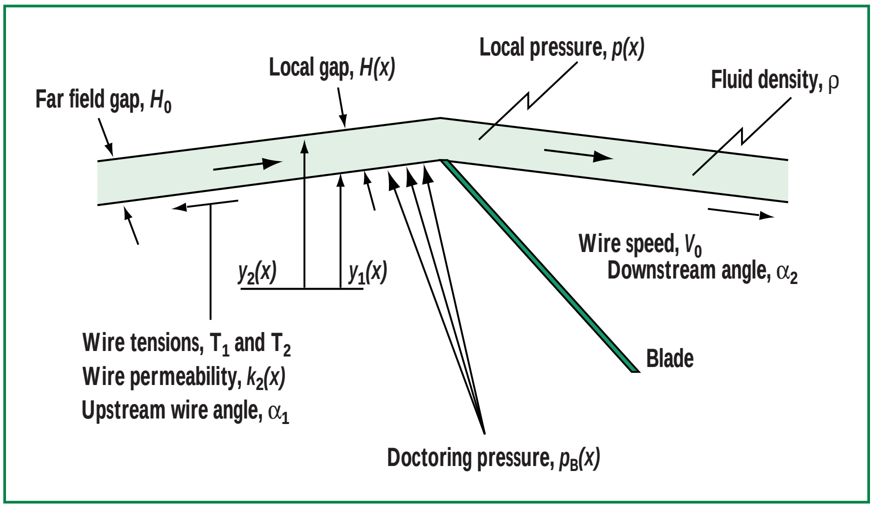
Finally, we recognize that the permeability is just one over the drainage resistance:

$$k_2 = 1/(\text{drainage resistance})$$

Combining the above three relationships, we derive Eq. 5, which supplements Eqs. 1–4.

$$k_2(x) = 1/\{C_4 + C_5[(y_2 - y_1)|_{\text{ref}} - (y_2 - y_1)|_x]\} \qquad (5)$$

Typical values of $C_4$ and $C_5$ can be inferred from a recent report by




***1. A simplified model of a single blade of a gap former, showing the important physical variables of the model***

Zhao and Kerekes *(7)*. (See Fig. 1 of that report.) Those values are $C_4$ = 12,500 Pa/(m/s) and $C_5$ = 26 MPa/(m$^2$/s).

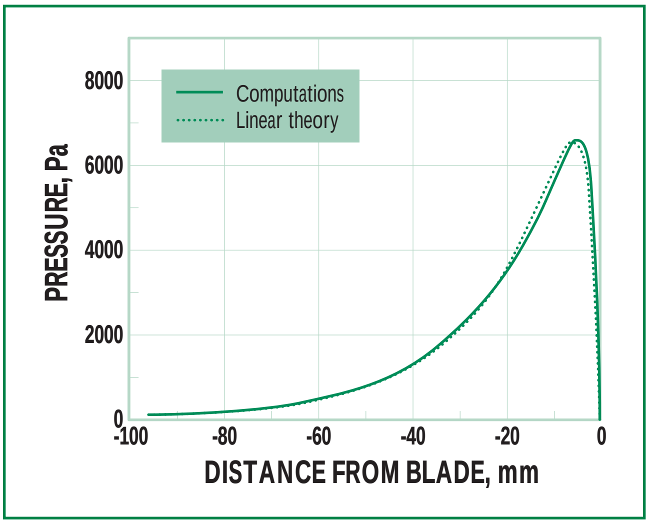
## COMPARISON WITH OTHER VERSIONS OF THE GOVERNING EQUATIONS

The governing Eqs. 1–5 presented here are similar to, but much more complete than, the equivalent equations solved by Zhao and Kerekes *(5)*. Their analysis neglects the centrifugal force acting on the wires, the viscous force acting on the fluid between the wires, and the bending stiffness of the wires, and it assumes that the quantities $V_F(x) - V_0$ and $H(x) - H_0$ are small. (Note that $H(x)$ is the local blade gap and $H_0$ is the far field gap.) Zhao and Kerekes also made a subtle error by using the differential form of the Bernoulli equation in their analysis. This form of the momentum equation fundamentally assumes that fluid leaving from between the wires leaves at the local fluid velocity, whereas more accurately it can be assumed to leave at the wire velocity. Inclusion of this effect results in the third term of Eq. 4. Zhao and Kerekes also assumed that the permeability of the wire and fiber mat is constant. Finally, they assumed that the underwire pressure caused by the stagnation point associated with the doctoring effect of a blade can be neglected.

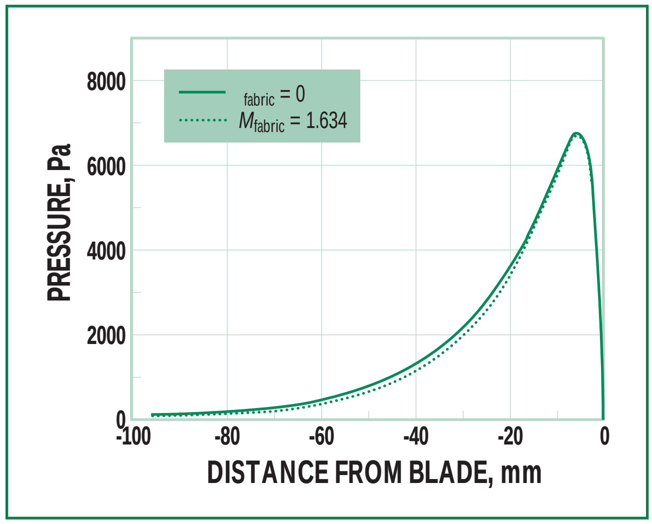
The equations solved by Zahrai and Bark *(6)* are similar to those solved here, but with the following differences. Zahrai and Bark, like Zhao and Kerekes, have neglected the centrifugal forces acting on the wires. In addition, Zahrai and Bark consider the flow between the fabrics as two-dimensional. They solve for the flow by means of a stream-function approach. Through their choice of a stream-function solution, Zahrai and Bark have implicitly assumed that the flow within the former is inviscid. Zahrai and Bark have also neglected the variation of wire and mat permeability with downstream distance and the doctoring effect of the blade.

## BOUNDARY CONDITIONS FOR THE EQUATIONS

The boundary conditions that apply to these equations are not obvious. Far upstream and far downstream of a blade—for the sample problem considered in the approximate analytical solution derived by Zhao and Kerekes *(5)* (hereinafter ZK) and in the present work—the wires are forced to make a prescribed angle to the horizontal. According to Eqs. 1 and 2, this constraint causes the far field pressure to be zero. It is straightforward to demonstrate that, if the bending stiffness is negligible,




***2. Influence of the linearization approximation on the computed pressure pulse***




***3. Influence of centrifugal force on the computed pressure pulse***

$V_F(x) = V_0$, $p(x) = 0$, $dy_1(x)/dx = \alpha_2$, and $dy_2(x)/dx = \alpha_2$ satisfy all five equations for $x > 0$ (downstream of the blade). (Note that $\alpha_2$ is the downstream wire angle.) At the blade itself, Eq. 1 is violated because of the point force applied by the blade, and hence we must solve the five equations over the domain $-\infty < x < 0$. For the complete problem, including the bending stiffness of the wires, Eqs. 1 and 2 are fourth order in both $y_1$ and $y_2$. We therefore need four boundary conditions for each of $y_1$ and $y_2$.

If the bending stiffness of the wires is negligible, Eqs. 1 and 2 are second order in $y_1$ and $y_2$, and only two boundary constraints on each of $y_1$ and $y_2$ are required. Those boundary conditions are:

$$y_1(0) = 0 \tag{6}$$

$$\frac{dy_2}{dx}(0) = \alpha_2 \tag{7}$$

$$y_2(-\infty) - y_1(-\infty) = H_0 \tag{8}$$

$$\frac{dy_1}{d}(0) = \alpha_1\left(\frac{T_1 + T_2}{T_1}\right) - \alpha_2\,\frac{T_1}{T_2} \tag{9}$$

Equations 6 and 8 arise from the problem statement. Equation 7 is true because, with zero pressure between the wires downstream of $x = 0$, the wires are straight from $x = 0$ to $x = \infty$. The boundary condition given by Eq. 9 can be derived by solving Eqs. 1 and 2 for $p$, integrating the resulting equality, and applying boundary conditions at $x = 0$ and $x = -\infty$.

For the complete problem, including the bending stiffness of the wires, these four boundary conditions (Eqs. 6–9) still apply. In addition, through manipulation of the governing equations, one can demonstrate that

$$\frac{d^3y_2}{dx^3}(0) = \frac{EI_1}{EI_2}\,\frac{d^3y_1}{dx^3}(0) \tag{10}$$

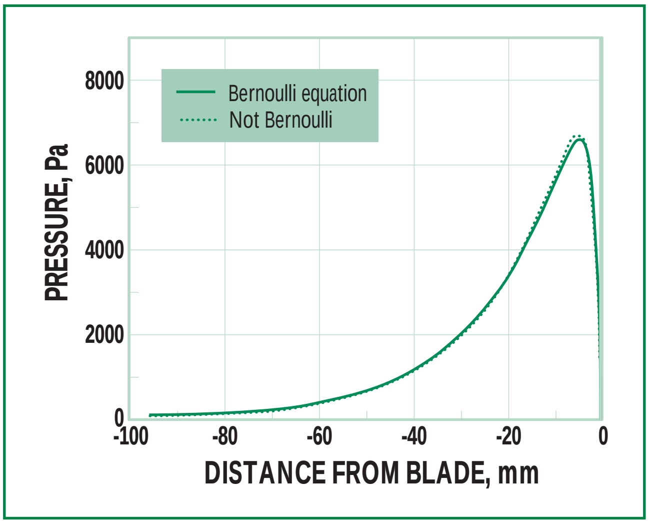
The other three boundary conditions imposed on $y_1$ and $y_2$ are satisfied provided that both variables asymptotically approach a straight line in the limit as $x \to \infty$. The boundary conditions on $p$ and $V_F$ are, as stated previously, $p(-\infty) = 0$ and $V_F(-\infty) = 0$.

## SOLVING THE EQUATIONS

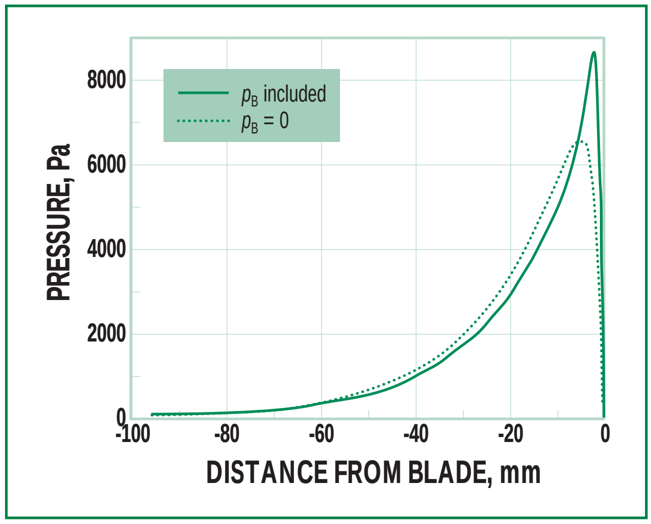
Equations 1–5 are five equations (more precisely, four coupled differential equations and one algebraic equation) in five unknowns. These equations are mathematically "stiff," i.e., they are very susceptible to numerical error. This stiffness of the equations means that they cannot be solved using conventional Runge–Kutta differential equation solvers. Rather, after much effort, it was established that the equations could be solved using a backwards Runge–Kutta integration step (i.e., integrating the equations in the upstream direction). This procedure has many advantages over downstream integration. The principal advantage is that one asymptotically approaches a final state as one integrates through the domain. If one integrates in the downstream direction, towards the blade, there is no such asymptotic limit to the variables.

For the problem in which the bending stiffness of the wires and the underwire pressure are both zero, five of the six boundary conditions of the problem are specified at $x = 0$ (Eq. 8 is the sole exception). It is then straightforward to use the "shooting method" to solve the two-point boundary-value problem: One guesses a value of $y_2(0)$, integrates the equations upstream towards $x = -\infty$, evaluates $y_2(-\infty) - y_1(-\infty)$, compares the value with $H_0$, and modifies the guessed value of $y_2(0)$ until Eq. 8 is satisfied.

Solving the governing equations including the wire stiffness is more complex. One must now guess several variables [e.g., $y_1''(0)$, $y_1'''(0)$, $y_2(0)$, and $y_2'(0)$, where, e.g., $y_1'' = d^2y_1/dx^2$], shoot towards $x = -\infty$, and modify




*4. Influence of Bernoulli equation approximation on the computed pressure pulse*




*5. Influence of underwire (doctoring) pressure on the computed pressure pulse*

one's guesses to satisfy all the boundary conditions at $x = -\infty$.

## RESULTS

ZK reported on the pressure pulses produced by an infinitesimal blade with $V_0$ = 16 m/s, $\alpha_1$ = 0.0124 radian, $\alpha_2$ = –0.0124 radian, $T_1$ = $T_2$ = 7000 N/m, $H_0$ = 0.0035 m, $EI_1 = EI_2 = 0$, and $k_2$ = 0.00005 m/s/Pa ($k_2$ was assumed constant in their model). That blade configuration, or one near it, was used as a basic case for study in the work presented here.

### *Influence of wire bending stiffness*

Zahrai and Bark *(6)* have shown that the effect of wire bending stiffness is negligible for bending stiffness values like those existing on operating twin-wire formers ($EI \approx 0.005$ N·m). The small effect of the bending stiffness can also be demonstrated by comparing the magnitude of the different terms in Eq. 1. For the test case mentioned here, the *EI* term is a maximum of 10% of the magnitude of the second term in the equation, and far less than 10% everywhere farther than a few millimeters from the blade. In view of these two observations, and because computations that include the bending stiffness are very time consuming, the wire bending stiffness will be neglected in subsequent discussions. A future report *(8)* will discuss modeling with bending stiffness included.

### *Influence of the linearization approximations*

As explained previously, Zhao and Kerekes *(5)* solved their governing equations by making two linearization approximations: $V_F(x) - V_0$ is small and $H(x) - H_0$ is small. **Figure 2** shows pressure-pulse results for the standard test case. Two curves are shown in this figure. The dashed curve is the pressure-pulse prediction of ZK, whereas the solid line is the computer model prediction with the centrifugal force and non-Bernoulli momentum equation effects set to zero (i.e., a very close approximation to the governing equations used by Zhao and Kerekes). Both models predict that, far from the blade, the pressure is nearly zero, and the pressure increases sharply near the blade to a peak pressure of about 6700 Pa. The pressure then falls very sharply to zero at the blade, and remains zero downstream of the blade.[1]

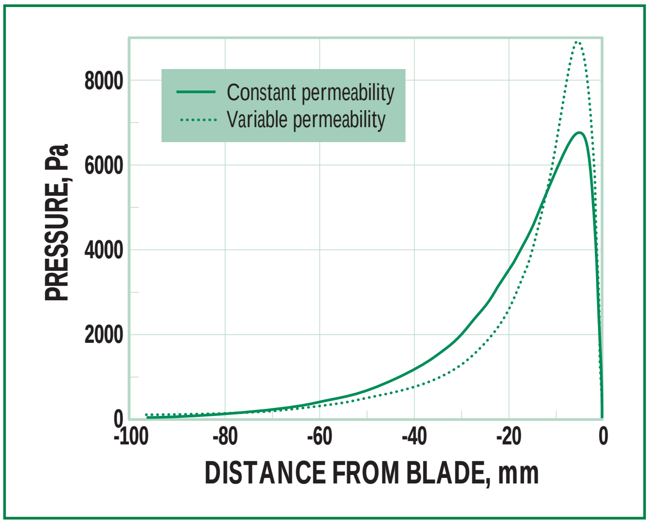
The agreement between the linearized theory and the exact computational simulation is remarkable: The peak pressure and pressure-pulse width are both predicted by the linear model to an accuracy of better than 2%. As one might anticipate, the disagreement between the ZK model and the computational model is greatest where the behavior deviates most from linearity (where $V_F - V_0$ and $H - H_0$ have the largest magnitude), i.e., very near the blade.

However, for different test conditions, the linearization approximation does produce more significant errors. For example, if the initial gap size is set to a small value, the linearized model predicts finite gap sizes at the blade, whereas in reality the two wires would contact one another owing to completion of the drainage.

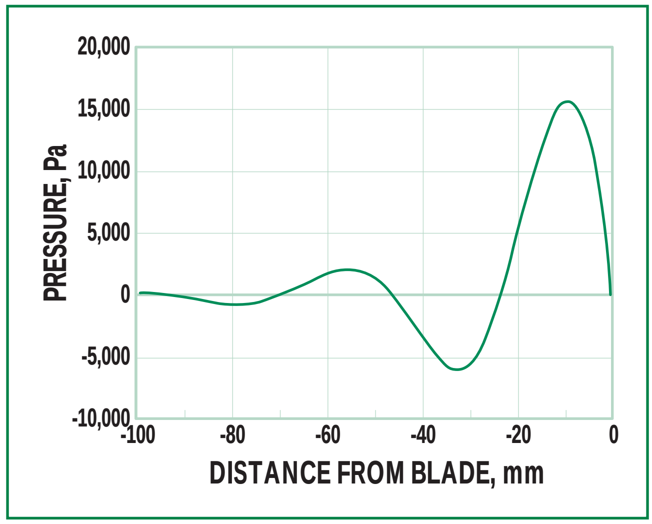
### *Influence of centrifugal force*

The area density of a piece of twin-wire fabric was measured to be $M_1 = M_2 = M_{fabric}$ = 0.415 kg/m$^2$. Saturated with water, as it would be in a paper machine, its density increases to $M_{fabric}$ = 0.634 kg/m$^2$. Finally, if one postulates that, owing to surface-tension effects, a layer of water up to 1 mm thick can adhere to the wire, one deduces that a maximum possible value of area density is $M_{fabric}$ = 1.634 kg/m$^2$. Recall that the centrifugal-force term appears in the governing Eqs. 1 and 2, with the tension term in the form, e.g., $(M_1V_0^2) - T_1$. Even assuming the maximum possible value of $M_1$, with $V_0$ = 16 m/s, the value of $M_1V_0^2$ is only 418 N/m, which is just 6% of $T_1$ (7000 N/m). One might

[1] The discontinuity in the pressure curve slope is a consequence of the zero wire bending stiffness. Wires of zero stiffness have a discontinuous slope where the wire contacts the blade. If the wire bending stiffness is finite, the pressure curve falls smoothly to zero a few millimeters downstream of the blade.




*6. Influence of variable permeability for the combined wire and mat on the computed pressure pulse*




*7. Oscillatory pressure distribution. The standard configuration ($\alpha_1$ = 0.0124 radian, $\alpha_2$ = 0.0124 radian, $T_1 = T_2$ = 7000 N/m, $H_0$ = 0.0035 m, $V_0$ = 16 m/s), except with $k_2$ = 0.00001 m/s/Pa.*

therefore anticipate that the calculated pressure pulse could be affected by as much as 6%. This value falls within the range of error (3% to 15%) estimated by Zhao and Kerekes *(5)*. In fact, for the standard test case, inclusion of the centrifugal-force term in Eqs. 1 and 2 reduced the peak pressure by just 1%, from 6665 Pa to 6612 Pa. The other effect of including the centrifugal-force term was the narrowing of the computed pressure distribution (curve depicting $M_{\text{fabric}}$ = 1.634 kg/m$^2$), as seen in **Fig. 3**.

### Influence of the more accurate momentum equation

Replacing the differential form of the Bernoulli equation with an alternative form (Eq. 4 without the $\tau_w$ term) causes the peak predicted pressure to be increased somewhat. For the standard test case, the peak pressure rose by 2%, from 6600 Pa to 6736 Pa, when the Bernoulli equation was replaced by the more appropriate form of the momentum equation. **Figure 4** shows that the difference in the computed pressure was very small farther from the blade, where the momentum lost by dewatering is less.

### Influence of wall shear stress

To study the influence of wall shear stress on the pressure pulses, the computational model was run with the $\tau_w$ term of Eq. 4 included. Three different cases were run to explore the effect of $\tau_w$. The viscosity was set first to $\mu = 10^{-3}$ N·s/m$^2$, then to $\mu = 10^{-2}$ N·s/m$^2$, and finally to $\mu = 10^{-1}$ N·s/m$^2$ ($\tau_w$ is directly proportional to the viscosity, $\mu$). The first value of the viscosity is that of pure water. The second value of viscosity—a factor of 10 higher—might account for the fact that the flow in the gap is neither fully developed nor necessarily Newtonian (owing to the presence of the fibers).[2] The highest value, which almost certainly does not occur in a real paper machine, was chosen to confirm the trend suggested by the intermediate value of $\mu$.

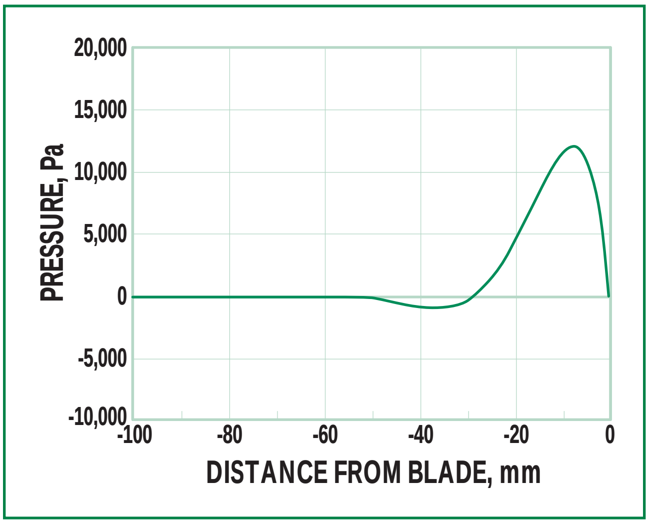
For something like the standard test case, the peak pressure was found to be 6630.5 Pa when neglecting the viscous term. Including the viscous term with $\mu = 10^{-3}$ N·s/m$^2$ reduced the peak pressure to 6629.5 Pa (a 0.02% difference). Increasing $\mu$ to $10^{-2}$ N·s/m$^2$ reduced the peak pressure further to 6621.0 Pa (a 0.2% change). Finally, increasing $\mu$ to values comparable with that of a good engine oil ($10^{-1}$ N·s/m$^2$) reduced the peak pressure only to 6540.2 Pa (a 1.4% change). Clearly, the influence of viscosity on the calculated pressure pulse is negligible.

### Influence of underwire pressure

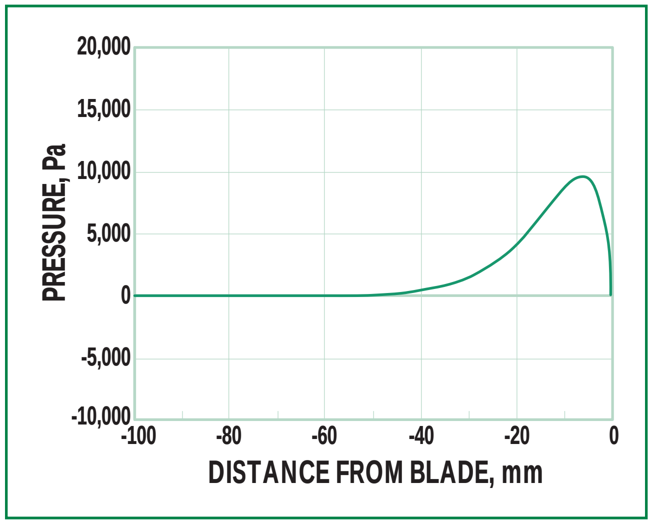
When fluid adhering to the underside of the bottom wire approaches the forming blade, it is forced to undergo an abrupt change of direction by the doctoring effect of the blade. Fluid right at the blade tip will come to very nearly the stagnation pressure ($p_0 = \rho V_0^2/2$), partially in order to achieve this direction change. This effect causes the pressure directly in front of the blade, on the underside of the wire, to differ from the suction-box pressure (which has heretofore been set to zero, so that the wire slope is constant far from the blade). To investigate the influence of this underwire stagnation pressure effect on the pressure pulse generated in a blade former, the underwire pressure, $p_B(x)$, was postulated to take the form $p_B(x) = p_0\exp(x/\lambda)$, where $\lambda$ is a length scale on the order of the adhering water film thickness.[3] We emphasize that this is an approximation adopted to study the effect of water doctoring. The pressure $p_B(x)$ is actually a function of the wire tension, the exact shape of the forming blade, the roughness of the wire surface, and the thickness of the adhering water layer. Therefore, the results

[2] It is likely to be laminar because, for most paper-machine geometries, the maximum Reynolds number based on gap size is about 1000, somewhat below the transition Reynolds number of 2300.

[3] Note that in the analysis $x < 0$, and therefore the exponential decays rapidly with distance from the blade.




*8. Same conditions as Fig. 7, except* **k$_2$** *increased to 0.00002 m/s/Pa*




*9. Same conditions as Fig. 8, except* **k$_2$** *increased further to 0.00003 m/s/Pa*

described here give only a sense (albeit a better sense than previous estimates have afforded) of the effect of the adhering water layer.

Even modest values of λ can have a significant effect on the calculated peak pressure. For example, with λ = 1 mm, the peak pressure is 25% higher (8400 Pa relative to 6700 Pa) than the λ = 0 mm case, as seen in **Fig. 5**. These findings prove that underwire pressure can have a substantial impact on the pressure pulse generated by a blade. Because the underwire pressure is a strong function of the exact shape of the forming blade [a slightly worn blade doctors less effectively, and thus produces a value of $p_B(0) < p_0$], this finding could explain why worn blades may produce poorer paper formation than do nonworn blades.

### *Influence of variable permeability for the combined wire and fiber mat*

As described previously, the combined permeability of the wire and the fiber mat decreases in the downstream direction because of fiber buildup on the mat.[4] Lower permeability is generally associated with higher peak pressures, and one would therefore suspect that allowing the permeability to change with downstream distance would increase the peak predicted pressure. This suspicion is in fact true. For approximately the standard case, if $k_2$ is fixed, the peak pressure calculated is found to be 6944 Pa. If one then allows $k_2$ to vary from the same fixed value upstream of the blade to a lower value near the blade (as given by Eq. 5), the peak pressure is found to be about 50% higher (10,700 Pa). For ease of future reference, we will refer to this particular analysis as the $k_{var}$ analysis. If one assumes that $k_2$ is constant, and equal to the average value of $k_2$, (predicted by the $k_{var}$ analysis) averaged over a distance of 100 mm upstream of the blade, the calculated peak pressure is 7500 Pa. Repeating the analysis with $k_2 = k_{var}$ (20 mm upstream average) yields a peak pressure of 9100 Pa. Finally, repeating the analysis with $k_2 = k_{var}$ (10 mm upstream average) gives a peak pressure of 9900 Pa. Since, at best, on a real paper machine one is able to measure the average $k_2$ around a blade, perhaps over a space of 20 mm upstream of the blade, this analysis implies that neglecting the variation in $k_2$ with distance is likely to produce an error of about (10,700 – 9,100)/10,700 = 15%.

**Figure 6** compares the pressure pulse for the standard configuration with the pressure pulse produced when the permeability is allowed to vary, but the average permeability (25 mm upstream average) is unchanged. The result shows that allowing the permeability to vary causes a substantial increase in the peak pressure in the pulp, consistent with the findings in the preceding discussion.

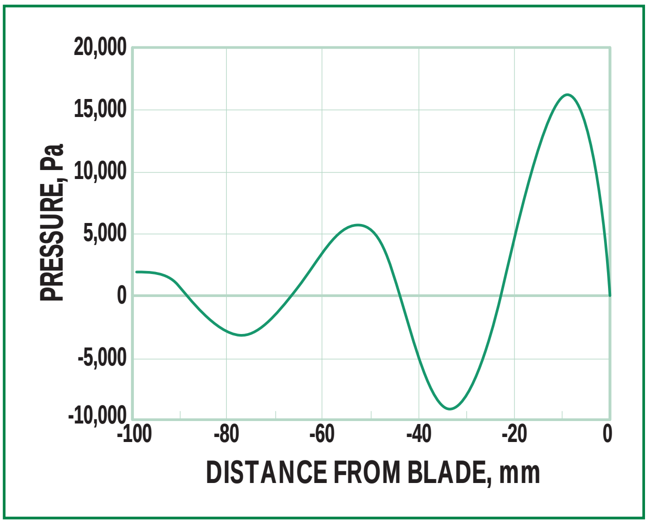
### *Pressure-pulse oscillations*

Zahrai and Bark *(6)* have predicted the existence of waves on the surface of wires upstream of a blade. These waves are associated with pressure oscillations upstream of the blade. Zahrai and Bark correctly describe these waves as analogous to capillary waves that form upstream of an obstacle in liquid with a free surface. In view of this understanding, the wave formation should be a function of the wire tension and the gap size. Through a more detailed analysis, Zahrai and Bark were also able to show that the amplitude of the pressure oscillations decreases with increasing permeability.

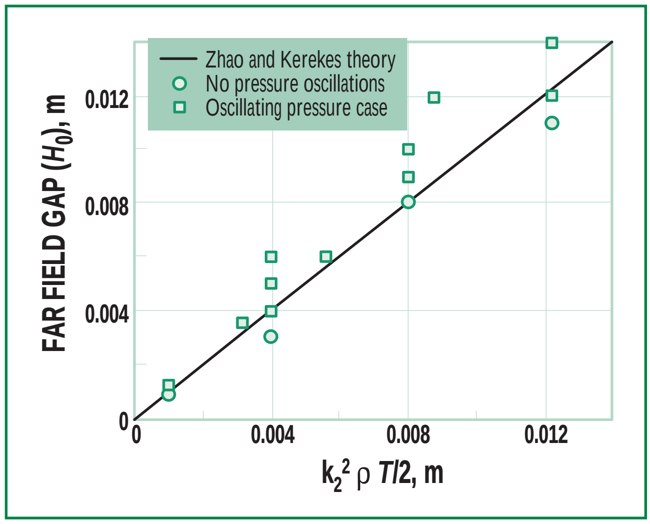
KEYWORDS

*Blades, computers, differential equations, dispersions, equations, gap formers, machine components, models, pressure, pulps, twin wire machines.*

[4] After the authors finished this research, they became aware of yet-to-be-published research by Moch *(9)* on the same topic.




*10. Same conditions as Fig. 7, except flow through mat set to zero where* **p** *< 0*




*11. Stability plot of pressure oscillations. Consistent with the theory of Zhao and Kerekes (the solid line), cases to the left of the line (*$H_0 > k_2^2\rho T/2$*) show pressure oscillations.*

The Zhao and Kerekes theory also predicts the existence of an oscillatory-pressure-field solution for certain paper-machine conditions, and in particular predicts that oscillations will occur if $H_0 > k_2^2\rho T/2$. **Figure 7** shows just such an oscillatory pressure distribution, computed for the standard test case with $k_2$ set to a small value ($1 \times 10^{-5}$ m/s/Pa). If $k_2$ is increased to $2 \times 10^{-5}$ m/s/Pa, the amplitude of the pressure oscillations decreases, as seen in **Fig. 8**. If $k_2$ is increased still further to $3 \times 10^{-5}$ m/s/Pa, the pressure field is essentially nonoscillatory, as seen in **Fig. 9**.

The continuity equation in the ZK linearized model is valid only if there is water outside the wires that can be sucked into the gap in locations where negative pressures occur between the fabrics. The computer model can simply set the flow rate through the wires to zero whenever a negative pressure occurs, and hence is not limited in the same way.

Setting the flow rate to zero in such cases is appropriate provided that surface tension prevents air from being sucked between the wires.[5] This zero flow rate is equivalent to making the wires locally impermeable. As we have seen, the amplitude of pressure oscillations increases as $k_2$ decreases, and therefore setting the flow rate to zero should increase the amplitude of the pressure oscillations. This supposition is confirmed by a comparison of Fig. 7 and **Fig. 10**.

To test the accuracy of the Zhao and Kerekes prediction that pressure oscillations occur if $H_0 > k_2^2\rho T/2$, a number of different test cases were run with different values of $H_0$, $k_2$, and $T$ ($\rho$ is essentially constant in all papermaking). The results are plotted in **Fig. 11**, which is a stability plot of the results. The solid line is the ZK stability criterion. Every set of variables below the line should be a configuration without pressure oscillations. Conversely, pressure oscillations should occur for variables that fall above the line. The Zhao and Kerekes theory is remarkably accurate. The ZK stability criterion is very nearly a best-fit line through the computational results.

The significance of these results to papermaking practice warrants mention. If an oscillatory pressure field actually occurs on a paper machine, the oscillations can have an adverse effect on the quality of the paper produced, since suction between the fabrics could lead to sheet disruption. However, the true effect of these oscillations on paper quality remains to be determined. Moreover, these oscillations probably do not occur often in practice because $H_0 > k_2^2\rho T/2$ only if $H_0$ is large or $k_2$ (or $T$) is small. In general, $H_0$ and $k_2$ are positively correlated; as the gap size decreases, so too does the permeability. It is therefore difficult simultaneously to have a large $H_0$ and a small $k_2$. The possible exception to this rule would be for a very high-grammage sheet.

The Zhao and Kerekes analysis, which is borne out by the computational simulation, predicts that oscillations will occur if $T$ is small. The model does not indicate whether $T_1$ or $T_2$ (or both) are predictors of pressure oscillations. To investigate this effect, we ran two different simulations. Both simulations had $V_0 = 16$ m/s, $k_2 = 0.00004$ m/s/Pa, $\alpha_1 = 0.0124$ radian, $\alpha_2 = -0.0124$ radian, and $H_0 = 0.006$ m. One simulation had $T_1 = 5000$ N/m and $T_2 = 9000$ N/m, and the other simulation reversed the two wire tensions (i.e., $T_1 = 9000$ N/m and $T_2 = 5000$ N/m). The two simulations produced very similar results (the ratio of negative to positive pressure peaks were respectively 21.6% and 21.8% for the two cases), which implies that some sort of average wire tension determines the stability of pressure pulses.

[5] If surface tension is insufficient to prevent air from being drawn between the wires where negative pressures occur, none of the single-phase flow analysis that has been used in this (and all other) models would be valid. One would then have to do an exceedingly complex multiphase flow analysis.

## CONCLUSIONS

A new computer model of the blade forming process has been developed. The new model has many features that are improvements on previous models of the blade forming process: For the first time, the effect of variable permeability for the combined wire and mat and the effect of underwire pressure have been computed, as have many other physical effects.

For characteristic machine conditions, the centrifugal-force term, the viscous-force term, the bending stiffness of the wire, and a more accurate momentum equation have only a few percent effect on the computed peak pressure developed upstream of a blade. In contrast, allowing the permeability of the wire and mat to change produces a 15% or greater increase in the peak pressure upstream of a blade. Doctoring by the blade can increase the peak pressure by about 20%, depending on the thickness of the water layer adhering to the lower wire.

Zhao and Kerekes have developed a model that predicts the existence of an oscillatory pressure field upstream of a blade for certain paper-machine conditions. (Oscillations are predicted if $H_0 > k_2^2 \rho T/2$.) The computational model confirms the prediction of Zhao and Kerekes and further shows that the upper and lower wire tensions play a nearly equal role in pressure oscillations.

The quality of the paper formation in a blade gap former is related to the pressure pulses generated by the blades. The model described here is an improvement in our understanding of the mechanisms of blade forming and is an important first step in the design of better blade gap formers. TJ

*Green is an associate professor in the Department of Mechanical Engineering at the University of British Columbia, Vancouver, BC, Canada V6T 1Z4. Kerekes is the director of PAPRICAN's Pulp and Paper Centre at the University of British Columbia, 2385 E. Mall, Vancouver, BC, Canada V6T 1Z4.*

*Received for review Dec. 11, 1996.*
*Accepted May 14, 1997.*

*Presented at the TAPPI 1996 Engineering Conference.*

## LITERATURE CITED

1. Bando, T., Sakamoto, K., Masuda, H., *et al.*, *TAPPI 1992 Pan-Pacific Pulp and Paper Technology Conference Proceedings*, TAPPI PRESS, Atlanta, Part A, pp. 213–220.
2. Iwata, H., Kuno, H., and Kuragasaki, M., *Japan Tappi Annual Meeting Proceedings*, Japan Tappi, Tokyo, 1991, pp. 108–111.
3. Sims, D. N., *TAPPI 1986 Twin-Wire Seminar Proceedings*, TAPPI PRESS, Atlanta, pp. 37–46.
4. Brauns, R., "Wet end developments," *CPPA 72nd Annual Meeting Preprints*, CPPA, Montreal, 1986, p. A275.
5. Zhao, R. H. and Kerekes, R. J., *J. Pulp Paper Sci.* 21(3): J97(1995).
6. Zahrai, S. and Bark, F. H., *Nordic Pulp Paper Res. J.* 10(4): 245(1995).
7. Zhao, R. H. and Kerekes, R. J., *Paperi Puu* 78(1): 36(1996).
8. Green, S. I., Zhao, R. H., and Kerekes, R. J., *J. Pulp Paper Sci.* (in press).
9. Moch, N., "On variable permeability during dewatering process in paper machines," Graduate thesis, Department of Mechanics, The Royal Institute of Technology, Stockholm, 1995.