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SYSTEM STABILITY OF THE OPEN DRAW SECTION AND PAPER MACHINE RUNNABILITY

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ABSTRACT

The present work is concerned with the system dynamics and stability of the open draw sections of paper machines where web breaks occur most frequently. We have applied a novel particle-based system dynamics model that allows the investigation of complex interactions between web property fluctuations and system parameters, without any constraints of a particular geometrical web shape or boundary conditions assumed *a priori*. The result shows that, at a given machine draw and web property parameters, the open draw section maintains its steady-state until it reaches a certain machine speed limit. At this speed the system looses its stability and the web strain starts growing without any limit, and thus leading to a web break. A similar instability can also be triggered when web properties suddenly fluctuate during steady-state operation. The parametric sensitivity studies indicate that, among the web property parameters studied, the elastic modulus of the wet web has the largest impact on the critical machine speed as well as on the detachment point where the web is released from the first roll. Further analysis shows that the decrease in dryness has a (negative) synergistic effect causing an

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increased risk of system instability. It is, therefore, most important to control, not only average dryness, but also its variations in order to enhance paper machine runnability.

1 INTRODUCTION

Web break is the major stumbling block for many of today's high-speed paper machines to achieve their maximum production efficiency. It has been long-recognized that the first open draw section (Fig. 1) is the problem area where the web breaks, or is first damaged causing subsequent breaks in the later sections of the paper machine. Accordingly, there have been considerable efforts made to understand web mechanics and dynamics of the open draw section from the early days of papermaking research [1, 2, 3, 4]. The most recent review has been given in [5]. Although the previous studies generated a number of important insights of the problem, one major limitation is that the results were often restricted to steady-state conditions. Web break, however, may not occur in the realm of steady-state, but may be induced by system instabilities. In addition, the analyses assumed a certain geometrical shape of the web and a web detachment condition from a roll *a priori*. As shown recently [6], constraining the solution and the detachment condition precludes many of the important phenomena in the open draw section.

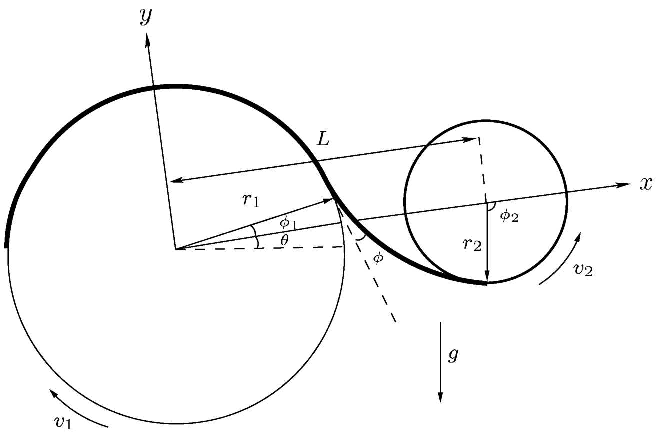

Figure 1. The open draw section. Paper web is transferred from the first roll to the second roll. This configuration may be seen between the second and third presses, the third and fourth presses (if it exists), or in the dryer section. The particular reference parameters used in the present work are: L = 1.38 m, r_1 = 0.8 m and r_2 = 0.5 m.

In this paper we apply the model given in [6], a particle system analysis, that precisely solves the full non-linear, system dynamics of the open draw section without any geometrical constraints imposed. The fact that the web detachment conditions depend on the web solution itself is fully taken into account. This approach is used to answer outstanding questions in the papermaking area: (1) how the open draw section becomes unstable in relation to machine speed, draw, fluctuations of web properties (e.g., adhesion strength, elastic modulus, and wetness), external perturbations, and system geometry, and (2) what factors define a safe operating window.

2 PARTICLE APPROACH

The paper web is treated as a series of point masses connected by visco-elastic elements (Fig. 2). We consider only movements in the xy-plane (Fig. 1) which allow us to apply a beam model. It is known that the continuum mechanics of a beam can be well represented by particle mechanics, see e.g. [6, 7, 8]. The particle approach leads to considerable simplifications by allowing full treatment of the complex web solutions. Except the restriction of planar dynamics, no further constraints need to be imposed. Here we provide only a brief outline of the model, the full details are given in [6]. A particle i is subjected to various interaction forces (internal and external). For example, the resulting elastic force f_i due to longitudinal stiffness is an internal force, as expressed by:

$$\boldsymbol{f_i} = \lambda_{i-1,i}\left(|\boldsymbol{r}_{i-1} - \boldsymbol{r}_i| - a_0\right)\boldsymbol{e}_{i,i-1} + \lambda_{i,i+1}\left(|\boldsymbol{r}_{i+1} - \boldsymbol{r}_i| - a_0\right)\boldsymbol{e}_{i,i+1} \quad (1)$$

where the $\boldsymbol{r}'s$ are positional vectors of the particles, the $\lambda's$ are local stiffness values and the $\boldsymbol{e}'s$ are unit vectors between the particles. Viscous effects are also accounted for by including longitudinal damping. The damping coefficients are related to the *kinematic viscosity v*. By assuming a certain paper thickness T, bending stiffness and its corresponding viscous effects are also included. Contact forces, gravity, and effects from air friction, air resistance and external perturbations can be included as well [6]. The total system of equations may be written in a compressed format as:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{dt}} = \begin{bmatrix} \chi_{11} & \chi_{10} & \chi_{12} & 0 & 0 & \cdots & 0 \\ 0 & \chi_{22} & \chi_{21} & \chi_{23} & 0 & \cdots & 0 \\ 0 & 0 & \chi_{33} & \chi_{32} & \chi_{34} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \chi_{N-1,N-1} & \chi_{N-1,N-2} & \chi_{N-1,N} \end{bmatrix} \mathbf{E}$$

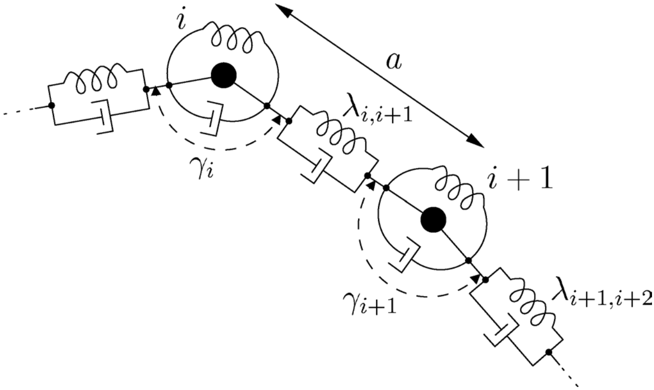

Figure 2. Topology of a modified Kelvin-Voigt visco-elastic model showing particles interacting through longitudinal stiffness and transverse bending stiffness. Also damping is indicated (both longitudinal and transverse).

where **P** is the total momentum vector, and the interaction matrix consists of both internal interactions χ_{ij} ($i \neq j$) and external interactions χ_{ii}. The vector **E** includes unit vectors for the external interactions as well as unit vectors connecting the particles of the paper web. Time-integrations were performed by the Richardson technique which yields precise velocities and position vectors for all the particles [6].

3 SYSTEM INSTABILITY OF THE OPEN DRAW

In spite of its simple configuration (Figure 1), the open draw section exhibits complex non-linear system dynamics behavior. A series of systematic simulations were performed to investigate the effects of machine speed, web properties and draw on the system dynamics. The reference values for the parameters used in the simulations are listed in Table 1. (See also the complete description given in [6].)

Table 1. Reference parameters for 45 g/m^2 (dry basis weight) newsprint. The listed values target 40 percent dry solids content.

v_{max} (m/min)	T (μm)	W_a (J/m^2)	draw κ	E (Pa)	ρ (kg/m^3)
1620	92	7.8	0.03	$3.5 \cdot 10^7$	1100

3.1 Instability induced by machine speed

When paper machine speed is increased, the operator naturally increases draw to maintain the take-off angle ϕ of the web (or the detachment point as expressed by the angle ϕ_1 in Figure 1). This practice is based on the common belief that operating at a high take-off angle may induce instability. Although the operator may not know exactly what kind of instability occurs, because it is dangerous to experiment such a condition with a real paper machine, this practice is the well-known wisdom of papermakers. Figure 3 shows a typical example of the effects of machine speed, where we plot the detachment angle ϕ_1 as a function of time. The draw was kept at a constant value 3% in all cases. Steady-state operation is seen for the speeds 1400, 1500 and 1600 m/min with falling detachment points ϕ_1 = 2.66°, –0.12°, and –5.57°. At each machine speed, however, ϕ_1 is constant over time. The total strain near the second roll (ε_T) equals the draw in all these cases which are typical for steady-state solutions. However, at 1700 m/min a new behavior emerges. The solution becomes transient: the detachment point starts to move further and further down the roll surface (Fig. 4). The length of the web increases and also its curvature, leading to additional stress due to both centrifugal and gravitational forces. The steady-state solution is lost and the strain ε_T starts to increase with time (Fig. 3, right figure). As long as the draw is kept *constant*, this is a typical phenomenon for the transient web strain. At a given set of web property parameters and draw, there is a critical machine speed (v_{max}), at which this transient behavior starts.

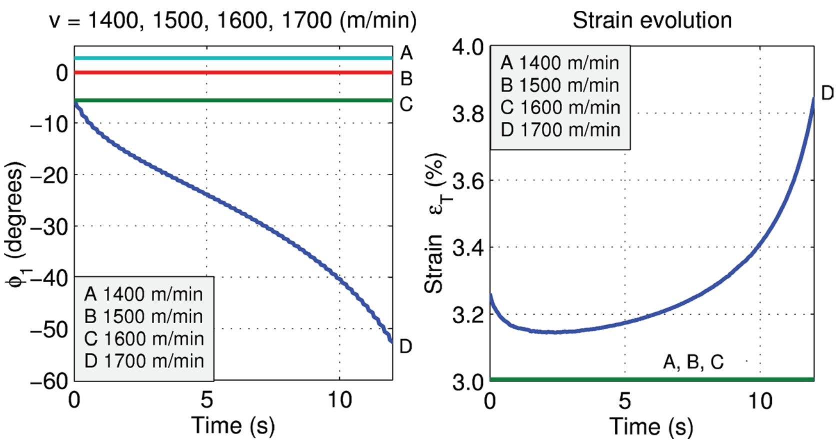

Figure 3. Evolution in detachment angle ϕ_1 and total strain ε_T as the machine speed is increased.

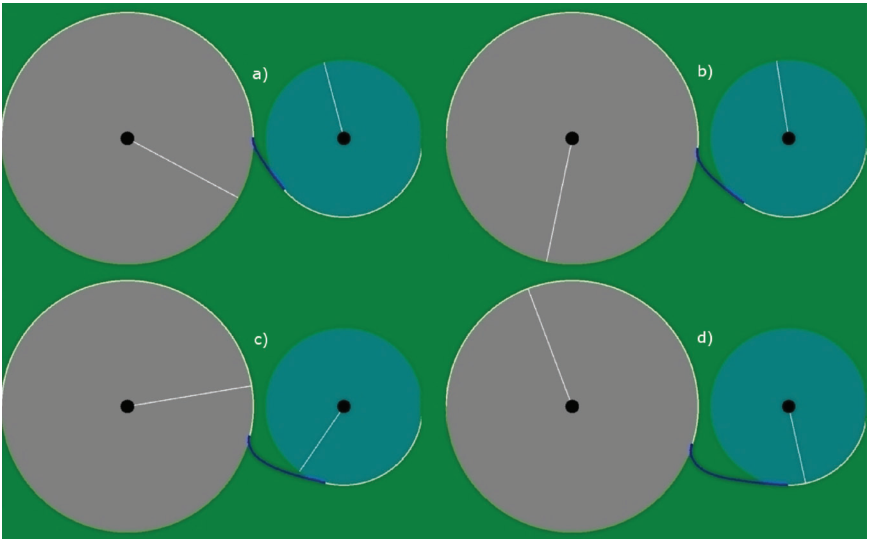

Figure 4. To aid interpretation of Fig. 3 we plot the length and the curvature of the paper web for the case D (in Fig. 3). The machine speed is 1700 m/min and snap shots are taken at t = 0.04, 0.26, 1.30 and 1.98 s. These are plotted in a), b), c) and d), respectively.

In order to obtain safe running conditions, a paper machine should be designed to have a sufficiently high critical machine speed (v_{max}). This ensures that the system will never come close to become transient. It is therefore of interest to study those parameters that can trigger the transient solution and their relative impact on v_{max}. The present work considers the following parameters: paper thickness (T), adhesion strength (W_a), draw (κ), elastic modulus (E) and mass density (ρ). Taking the total differential of v_{max} (T, W_a, κ, E, ρ), we find:

$$dv_{max} = \frac{\partial v_{max}}{\partial T}dT + \frac{\partial v_{max}}{\partial W_a}dW_a + \frac{\partial v_{max}}{\partial \kappa}d\kappa + \frac{\partial v_{max}}{\partial E}dE + \frac{\partial v_{max}}{\partial \rho}d\rho \quad (2)$$

By approximating Eq. 2 with finite differences and rearranging the expression, we obtain the machine speed sensitivity formula:

$$\frac{\triangle v_{max}}{v_{max}} = c_T\frac{\triangle T}{T} + c_{W_a}\frac{\triangle W_a}{W_a} + c_\kappa\frac{\triangle \kappa}{\kappa} + c_E\frac{\triangle E}{E} + c_\rho\frac{\triangle \rho}{\rho} \quad (3)$$

where the coefficients c_T, c_{W_a}, c_κ, c_E and c_ρ are calculated from the slopes in Fig. 5 around the reference values given in Table 1. The result showed that $c = [c_T, c_{W_a}, c_\kappa, c_E, c_\rho] = [0.054, -0.11, 0.71, 0.63, -0.45]$. From the vector c we see that the high impact factors on v_{max} are draw (κ), elastic modulus (E), and sheet density (ρ). For example, the higher the elastic modulus, or the lower the density, the higher the v_{max}. In the papermaking area it is more common to consider grammage ($g = \rho T$) instead of mass density. Then the term $c_\rho \frac{\triangle\rho}{\rho}$ in Eq. 3 is replaced by $c_g \frac{\triangle g}{g}$, where $c_g = c_\rho$ and $\triangle g = T\triangle\rho$ since a possible

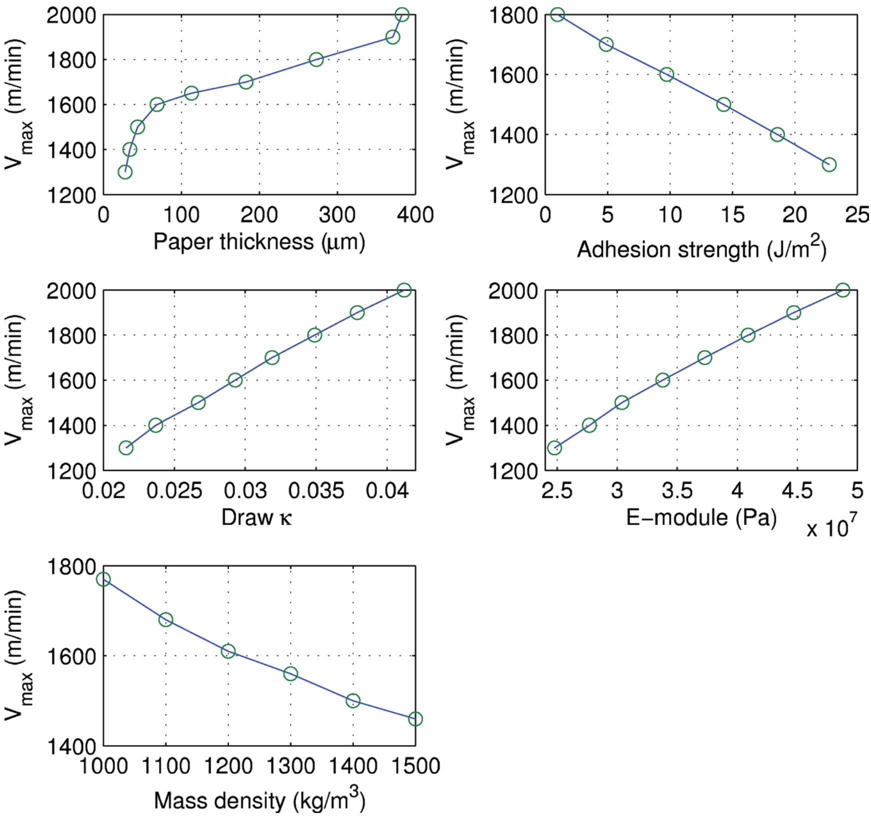

Figure 5. The maximum machine speed vs. various system/material parameters of the open-draw. At a given value of each parameter, an open draw section becomes unstable when the machine speed exceeds v_{max}.

change in paper thickness T is already accounted for. By assuming a constant draw ($\triangle\kappa = 0$) and dropping the small contribution from the first term ($c_T = 0.054$), we have $\frac{\triangle v_{max}}{v_{max}} \approx c_{W_a}\frac{\triangle W_a}{W_a} + c_E\frac{\triangle E}{E} + c_g\frac{\triangle g}{g}$. It is interesting to see how v_{max} depends on dry solids content. For example, $\triangle W_a = \frac{\triangle W_a}{\triangle x}\triangle x$, where x is dryness. From the adhesion study by Mardon (Fig. 22 in [9]) we find the estimate $\triangle W_a / W_a \approx 3\triangle x$ in the neighborhood of $x = 0.4$. In the same way (using ref. [3]), we estimate $\triangle E/E \approx 7\triangle x$. By definition, the grammage $g(x) = g(1)/x$ which then gives $\triangle g/g = -\triangle x/x$. Together with the numerical values c_{W_a}, c_E, c_g, we thus find:

$$\frac{\triangle v_{max}}{v_{max}} = -0.33\triangle x + 4.4\triangle x + \frac{0.45}{x}\triangle x \qquad (4)$$

For example, if dryness is increased with $\triangle x = 0.05$ this estimate predicts about a 25% increase in v_{max}. Clearly there is a large impact of dryness on the critical speed.

3.2 Instability induced by the fluctuations of web properties and draw

In real operation, the properties of the wet web entering the open draw section are constantly fluctuating at various frequencies. Some examples are mass density, wetness (or dry solids content), elastic modulus, thickness and adhesion strength. Therefore, the simulation parameters detailed above should be regarded as time-dependent variables. Figure 6 is one of such examples where a sudden increase in the mass density (either by fibre or water) is introduced for certain time durations. After a short transient behavior from the start of the simulation, the strain ε_T reaches its equilibrium value of 3% (which equals the draw κ). At $t = 5$ seconds, when the mass density is suddenly increased by 15%, there is a sharp increase in the strain. Depending on the duration of this mass density perturbation, the transient behavior is quite different: For the durations of 5.0 s and 7.5 s (cases A and B), the strain ultimately restores its initial value of 3%. However, the transient behavior becomes irreversible for a duration longer than 7.5 s, i.e., steady-state operation is not restored. Besides an increased density, the transient behavior can also be triggered by a decrease in elastic modulus (see [6]) or an increase in adhesion strength.

In Fig. 7 we show the strain behavior for the case of a sudden decline in elastic modulus by 15 percent at t = 5 s, but a machine speed of only 1400 m/min. The elastic modulus is then kept at this lower level until it becomes

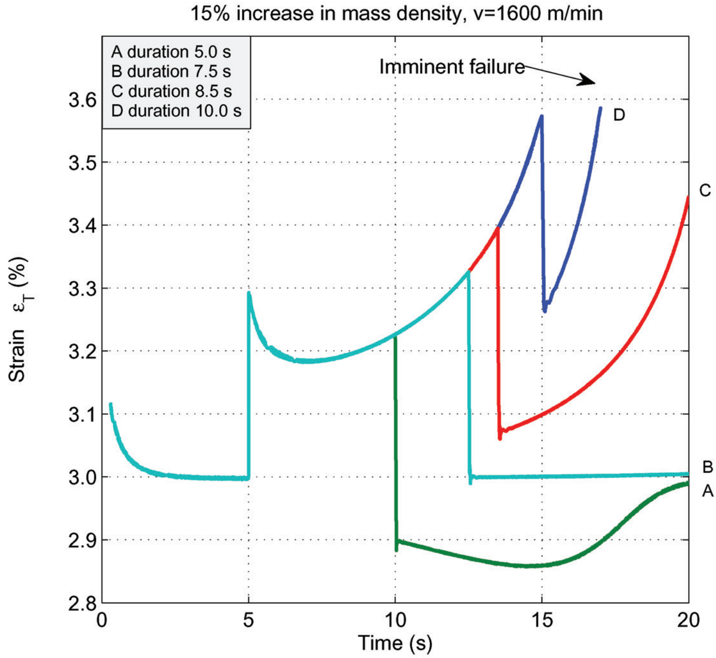

Figure 6. Total strain ε_T as a function of time for v = 1600 m/min. The mass density is suddenly increased by 15% at t = 5 s. This perturbation is maintained during the periods 5, 7.5, 8.5 and 10 s after which the perturbation is turned off (i.e., the original density is restored).

restored at t = 10 s. In the upper figure we see sudden surges in the strain and then fast relaxations back to steady-state. This happens only at times of a sudden change in the elastic modulus, i.e, at 5 s (overshoot) and at 10 s (undershoot). On the other hand, the detachment point (the lower figure), as expressed by release angle ϕ_1, decreases to about –4 degrees and then remains until the elastic modulus is restored at t = 10 s. It is clear that ϕ_1 contains important information of the web property fluctuations. This will be shown in detail in the next section.

In the above two cases (Figs. 6 and 7) the web properties were changed in a step-wise manner. However, the response in web strain may depend on the rate of change in the web properties, e.g., the elastic modulus. For example, if the elastic modulus changes very slowly, the relaxation of the strain might be sufficient enough to avoid a dangerous strain evolution. To investigate this effect, we changed the elastic modulus according to $E\,(t - t_i) = E_0\,\exp^{-\tau(t - t_i)}$,

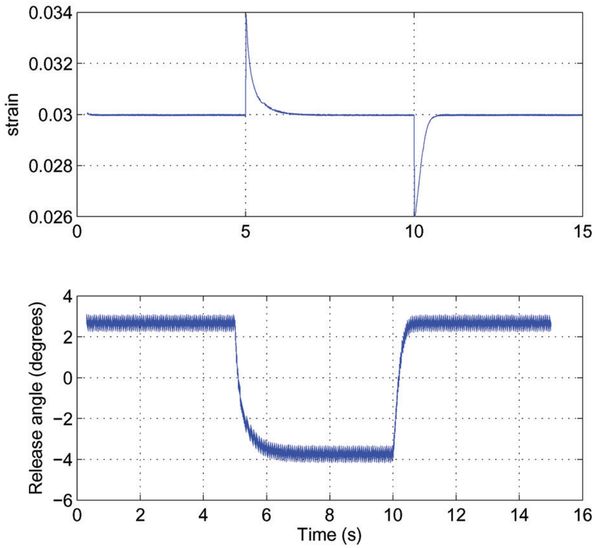

Figure 7. Total strain ε_T response for v = 1400 m/min. A sudden 15% decrease in the elastic modulus occur at t = 5 s. At t = 10 s it is restored. The corresponding evolution in the detachment point, as expressed by the release angle ϕ_1, is also shown.

where t_i is the time when the perturbation starts, E_0 is the original elastic modulus (unperturbed modulus), and τ is chosen such that when $t = t_f$, the elastic modulus has declined by 15 percent. After $t = t_f$, the elastic modulus is kept constant ($= 0.85E_0$). Figure 8 shows the simulation results for various durations $\triangle = t_f - t_i$. In overall, a fast change results in a more dramatic and dangerous response, while a slow change is much more forgiving.

In Fig. 9, the results for a higher machine speed of 1600 m/min are shown. The overall picture is substantially different due to the presence of transient solutions (c.f. Fig. 6). In this case the perturbations were turned off at t = 10 s. Despite this, some of the solutions do not relax back to the steady-state strain and eventually lead to a system instability, as was also observed in Fig. 6.

In Fig. 10 we study the effect of an sudden increase of the adhesion strength. The web initially shows some relaxation, but due to the rather high speed of 1600 m/min, the transient behavior soon starts to dominate, which subsequently leads to the system instability.

Similarly to the fluctuations of the web properties, the perturbations of external conditions, such as draw variations, aerodynamic effects, the

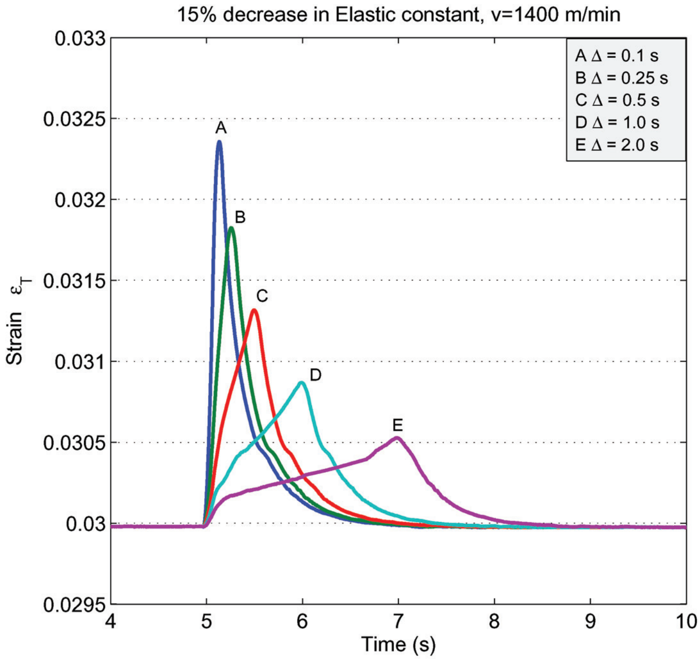

Figure 8. Total strain ε_T as a function of time for v = 1400 m/min. Elastic modulus starts to decline at $t_i = 5\ s$ (see text) and this decline is fully developed at $t = t_f$. A given curve thus shows the response in ε_T depending on how fast the elastic modulus declines from its original value E_0. The legend gives the various values of $\triangle = t_f - t_i$.

vibrations of the rolls, temperature, etc., can affect the system stability. Figure 11 is one of such examples where the draw is suddenly decreased from 3% to 2.8% at t = 5 seconds. This low draw level eventually triggers the transient behavior through a longer web path and higher centrifugal forces.

4 FACTORS CONTROLLING DETACHMENT POSITION

It is sometimes claimed by papermakers that the fluctuations in the detachment angle ϕ_1 of the first roll reflect some types of the system stability. Its variations certainly depend on several variables including web property fluctuations, system fluctuations, and aerodynamic effects. We shall here study several variables and show that only a few of these dominate the behavior. Analogously to the previous considerations (Eq. 3), we may write:

$$\frac{\triangle\phi_1}{\phi_1} = c_E\frac{\triangle E}{E} + c_{W_a}\frac{\triangle W_a}{W_a} + c_T\frac{\triangle T}{T} + c_\rho\frac{\triangle\rho}{\rho} + c_\kappa\frac{\triangle\kappa}{\kappa} + c_v\frac{\triangle v}{v} \tag{5}$$

After a similar analysis as that given in Fig. 5, we obtained the following values for the coefficients $c = [c_E, c_{Wa}, c_T, c_\rho, c_\kappa, c_v] = [10.8, -4.5, 2.8, -5.2, 10.7, -13.2]$. As before, E is the elastic modulus, W_a is the adhesion strength, T is the paper thickness, ρ is the mass density of the wet sheet, $\kappa = (v_2 - v_1)/v_1$ is the draw, and v is the machine speed. At a given relative change in these parameters, elastic modulus, draw, and machine speed has the largest effect on the detachment point, and surprisingly, adhesion strength has a rather modest effect.

Dryness variations influence several of the above parameters. In the case of wet newsprint a typical dry solids content x is about 0.4. For example, assume

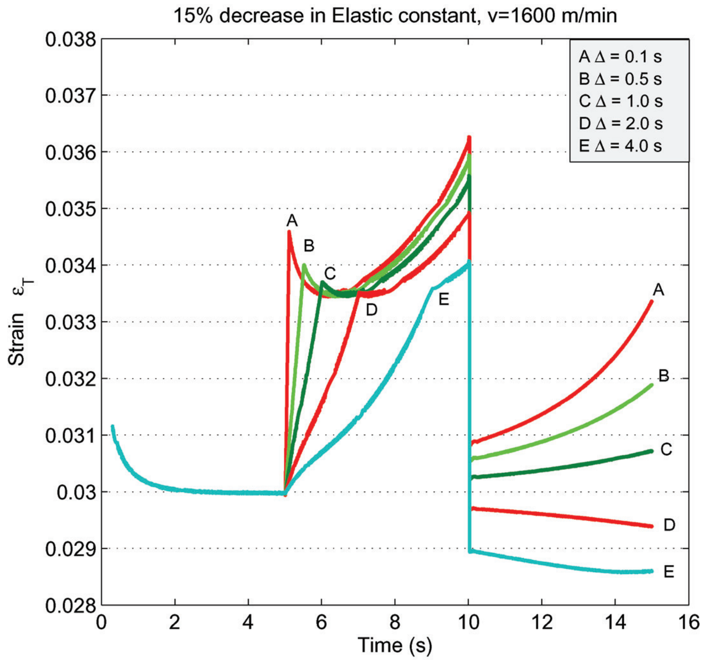

Figure 9. Total strain ε_T as a function of time for v = 1600 m/min. Elastic modulus starts to decline at $t_i = 5\ s$ (see text) and this decline is fully developed at $t = t_f$. A given curve shows the response in ε_T depending on how fast the elastic modulus declines from its original value. At t = 10 s the elastic modulus is restored to E_0. The legend gives the various $\triangle = t_f - t_i$.

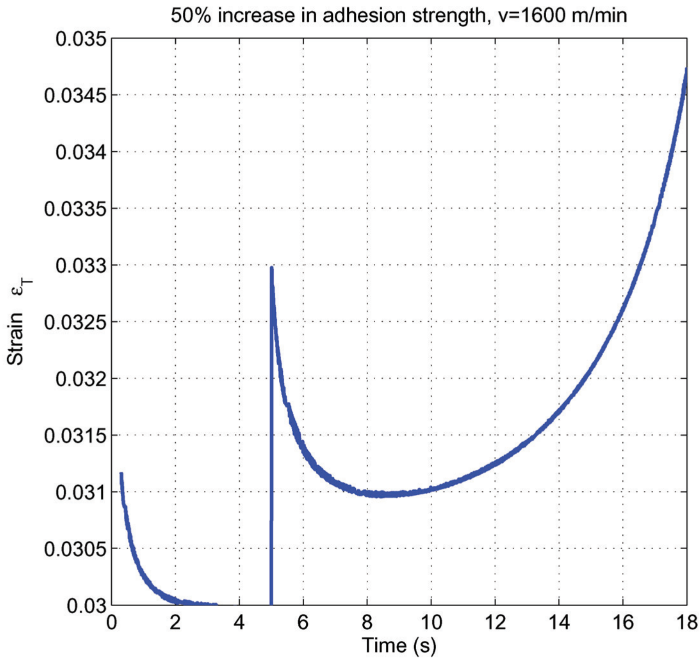

Figure 10. Total strain ε_T as a function of time for $v = 1600$ m/min. The adhesion strength is increased by 50% suddenly at $t = 5\ s$ and then kept constant. (The initial drop in total strain for $t < 2$ s is simply an artifact caused by the transition from an initial straight web condition into the actual physical solution.)

that there are variations in the dryness from time to time according to $x = 0.4 \pm 0.05$. It is well known that the elastic modulus is quite sensitive to dryness variations (e.g., [10]). Following the same argument (see Eq. 4), we estimate that $\triangle E/E \approx 0.35$ for newsprint when the dryness x is increased by 0.05. Similarly, an estimate from Fig. 22 of [9] gives that $\triangle W_a/W_a \approx 0.15$. We also find that $\triangle T/T \approx -0.08$ and $\triangle \rho/\rho \approx -0.03$. These last two estimates are based on the model provided in the Appendix. A similar expression as that in Eq. 4 may then be obtained. The angular dependence to a dryness change $\triangle x$ thus becomes:

$$\frac{\triangle\phi_1}{\phi_1} = c_E\frac{\triangle E}{E} + c_{W_a}\frac{\triangle W_a}{W_a} + c_T\frac{\triangle T}{T} + c_\rho\frac{\triangle\rho}{\rho} = 75.5\triangle x - 13.5\triangle x - 4.5\triangle x + 3.1\triangle x \quad (6)$$

This formula is valid in the neighborhood of $x = 0.4$ and we have assumed

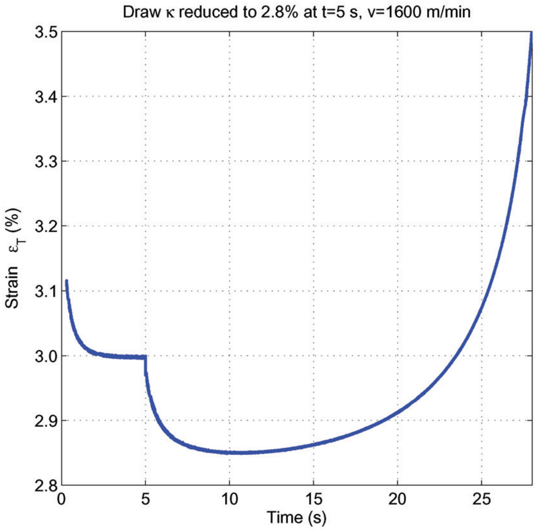

Figure 11. Total strain as a function of time. The system draw κ is decreased from 3.0% to 2.8% at t = 5 s.

that the system draw κ and machine speed v are kept constant. We see that during normal operation it is the variations in elastic modulus (first term) that shows the largest influence on the detachment angle ϕ_1.

5 EFFECTS OF OPEN DRAW DISTANCE

A long open draw is often considered to be a cause of various instability problems by papermakers. Therefore, there has been a consistent trend of shortening the open draw, and finally closing the draw completely. To the authors' knowledge there is no quantitative and comparable data for the effect of shortening the draw on paper machine runnability, but experiences are pointing toward a positive effect of this modification. In this section we investigate how shortening the draw affects the system dynamics of the open draw and its stability.

Simulations were performed with the same data set as in Table 1 and with a machine speed of 1400 m/min. Figure 12 shows the length of the web in the open draw, L_w, as a function of the distance between the roll surfaces. As the roll surfaces approach each other, the web length decreases (see also Fig. 13).

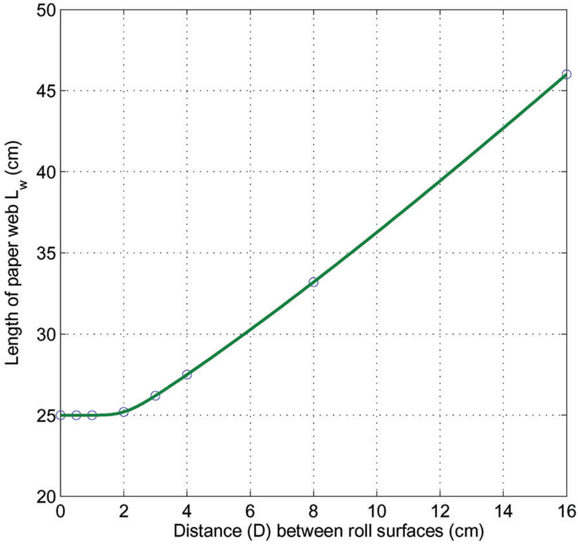

Figure 12. The length L_w as a function of the distance D between the roll surfaces ($D = L - r_1 - r_2$) in the open draw section, see Fig. 1 for notation. Kinematic viscosity: $v = 30\ m^2/s$.

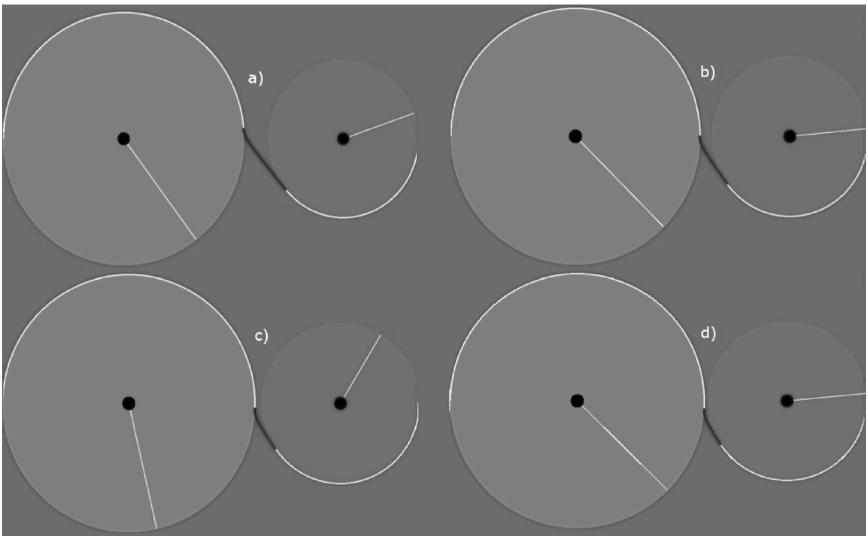

Figure 13. The length of the paper web (L_w) is shown for the distances D plotted in Fig. 12 to aid interpretation. D=16, 8, 4 and 2 cm are plotted in a), b), c) and d), respectively. $D=L - r_1 - r_2$, see notation in Fig. 1.

However, it should be noted that the web length does not continue to decrease, but reaches a limiting value (about 25 cm) at a roll surface distance of 2 cm. This limit changed slightly to 18 cm when the kinematic viscosity parameter was altered from 30 m^2/s to 10 m^2/s. More importantly, the roll surface distance influences the machine stability parameter, the critical speed v_{max}: With a decreasing roll surface distance, the critical speed also *decreases* (Figure 14). This implies that, although the effect is minor, shortening the draw has no beneficial effect from the point of the system stability of an open draw section.

The above result may seem to contradict the general experience. However, at present, there are no results that proves or disproves the above simulation result to the authors' knowledge. The real positive effect of shortening the draw may come from reducing aerodynamic disturbances by decreasing the exposed web length, or from reducing the time of flight spent in the open draw (thus reducing the probability of web breaks).

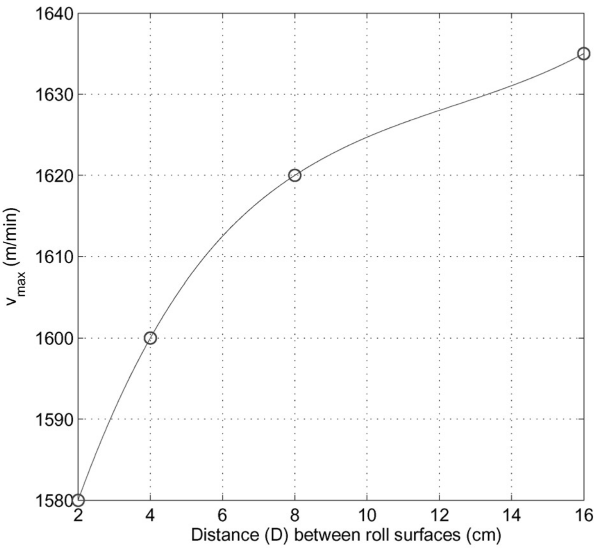

Figure 14. The critical speed dependence of the open draw distance. As the rolls approach each other (D= $L - r_1 - r_2$), there is a slight decrease in v_{max}. Kinematic viscosity: $v = 10\ m^2/s$.

IMPLICATIONS FOR OPERATORS

Based on the findings in the present work we provide the following specific information and suggestions for improving the operation of a papermachine.

- Dryness, including its average and variation, is most important in maintaining web stability in the open draw section.
- The dryness variations are caused by the changes in:
  - drainage characteristics of furnishes (composition, broke content, freeness etc.)
  - retention (wet-end disturbances, retention aids, and other chemicals)
  - steam box stability
  - wire/felt permeability (or cleanliness)
- Generally, a quick excursion of dryness to a lower value and its continuation are dangerous. Slow variations are acceptable.
- The position of the release point is a good indicator of wet-end fluctuations, and thus should be monitored.
- An "optimum" release point is difficult to define and machine-specific, since it depends on the machine and wet web properties mentioned earlier, which may also be determined according to end-use requirements.
- When the release point fluctuates, it can be controlled by draw. However, it is best to simultaneously identify the cause of the fluctuations in the wet-end. (Fix the problem from the source.)

CONCLUSIONS

We have applied a novel particle approach to investigate the system dynamics of the open draw section. The model could display rich phenomena of nonlinear dynamics of the open draw. The model predicted, for the first time, various instability phenomena that papermakers observe in their operation. The model also provided quantitative information for stable operation to improve paper machine runnability. The main conclusion of this study is that dryness and its fluctuations are critically important in controlling the system stability of open draw sections.

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APPENDIX

ESTIMATE OF CHANGES IN THICKNESS AND DENSITY DUE TO DRYNESS CHANGES

With regard to the wet mass density there are complications due to a possible air content of the wet sheet and sparse experimental data. We therefore develop the following model. By assuming that the density of air ρ_4 is negligible, the total mass density of a sheet divided in four layers becomes:

$$\rho(x) = \frac{\rho_1 T_1 + \rho_2 T_2 + \rho_3 T_3(x)}{T(x)} \tag{7}$$

where x is the dryness and the ρ_1, ρ_2, and ρ_3 are the mass densities of dry fibers, dry fillers and water. The sheet thickness is $T(x) = T_1 + T_2 + T_3(x) + T_4(x)$ where T_1, T_2, T_3, and T_4 respectively are the dry fiber thickness, dry filler thickness, water thickness and air thickness, respectively. We introduce $\rho_1 T_1 + \rho_2 T_2 = \rho_{eff}\,(T_1 + T_2)$, so that $\rho_{eff} = w_1\rho_1 + w_2\rho_2$ ($w_1 = T_1/(T_1 + T_2)$ and $w_2 = T_2/(T_1 + T_2)$, i.e., in volume percent), and the grammage is $g(x) = \rho_{eff}\,(T_1 + T_2) + \rho_3 T_3(x)$. For $x = 1$ we have $T_3(1) = 0$ since there is no water in the sheet. Thus the effective thickness of the dry substance is

$$T_1 + T_2 = \frac{g\,(1)}{\rho_{eff}} \tag{8}$$

We may then write $g\,(x) = g\,(1) + \rho_3 T_3(x)$, and since, by definition, $g\,(x) = g(1)/x$ we have:

$$T_3\,(x) = \frac{g\,(1)}{\rho_3}\frac{1-x}{x} \tag{9}$$

In the case of $T_4(x)$, we have that at $x = 1$, $T_4(1) = T\,(1) - T_1 - T_2$ (no water). At some point $x = x_d$, the sheet is saturated with water so $T_4\,(x_d) = 0$ (no air). By introducing a linear relationship we write:

$$T_4\,(x) = T_4\,(1)\,\frac{x - x_d}{1 - x_d} \tag{10}$$

We apply the following parameters obtained from a Swedish newsprint machine: $\rho_1 = 1200\ kg/m^3$, $\rho_2 = 2500\ kg/m^3$, $\rho_3 = 1000\ kg/m^3$, $w_1 = 0.92$, $w_2 = 0.08$, $g(1) = 0.9 \times g(0.9) = 0.9 \times 0.045\ kg/m^2$, $x_d = 0.4$, and $T(1) = 75{\cdot}10^{-6}m$. We can then evaluate the sensitivities, e.g., $\triangle\rho/\rho \approx (1/\rho)\,(d\rho/dx)_{x\,=\,0.4}\,\triangle x \approx -0.03$, where $\triangle x = 0.05$. In the same way, $\triangle T/T \approx -0.08$. The selected value $x_d = 0.4$ used in Eq. 10 turned out to be unimportant, because both $\triangle\rho/\rho$ and $\triangle T/T$ were practically constant for the range of values $0 \le x_d < 0.4$.

Transcription of Discussion

SYSTEM STABILITY OF THE OPENDRAW SECTION AND PAPER MACHINE RUNNABILITY

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Keith Good Oklahoma State University

I found all the modelling quite interesting. What I wondered was, it seems to be the release point that is important in dictating the centrifugal stresses that are seen by the web. Is anybody trying to watch the release point with video as you did, and then use that as a trim signal to the velocity of the downstream drives and control the release point?

Sverker Edvardsson

Yes, we do in some paper mills. I know in our city, there is one mill where they actually have done this. So they are changing draw in order to keep the release point at a certain position, fixed all the time. And in their experience they get a much more stable system with less web breaks. What we have seen here is just an explanation of what might be going on.

Anders Åström Aylesford Newsprint (from the chair)

Maybe I can add to that as well. We at Aylesford have tried to do exactly that and use the measured position of the release point, but have not succeeded because of difficulties in actually measuring the release position. The difficulty is getting the measuring equipment into a good position in the machine environment.

Discussion

Steve I'Anson University of Manchester

Would it be possible to control the release point, for example by putting release agents onto the centre roll? So perhaps at lower speeds, you could start by applying some release agents and turn them down as the speed went up?

Sverker Edvardsson

Yes, they already put release agents on the roll. Talking to some operators, it was not clear how important it was, because at one point the technical system failed and they noticed two weeks afterwards that it had been running beautifully with no release agent. So, in that case, it was not so important. But they also run at quite low speeds, around 1400 m / minute, whereas the effects I am talking about are when you are pushing your machine. I know they are tuning the machines today to run faster in the future and then problems like this could arise. Well, if you could decrease adhesion when you run fast, then you would be in a much better situation. That is true!

Lars Wågberg KTH

I would like to continue with the earlier question on adhesion, because I think your work is very relevant, according to my experience, to what is the most critical factor for creating both good runnability and optimized paper properties. When we talk about adhesion, we often think about molecular adhesion, but what I think we are talking about here is capillary adhesion, which means that the roughness, i.e. micro-roughness on the roll, will make the paper stick to the roll and it is not so much chemical adhesion we are studying. This means that the structure of the roll is very important, I guess.

Sverker Edvardsson

I think it could be several factors, since many mills use release agents, which involve chemistry. So they must have seen that it is helpful for certain surfaces, but it is true that the roughness is extremely important and so is the moisture of the paper web, the adhesion changing dramatically, depending on moisture.

Lars Wågberg

Yes, of course it can be chemical adhesion, but release agents also decrease the surface tension. Nevertheless, thank you for your good and relevant work.

Tetsu Uesaka FPInnovations and co-author

Just adding to the comment on release point. The release point is certainly important for control, but it is not the cause of the break, but it is the effect indicating the stability of this system. So we should not focus on just the release angle or release point – this is the effect, not really the cause. Even if you can perfectly control the adhesion, there is an overwhelming effect of the upstream side of the stability variation, that is most important. That is really the issue of this paper: machine runnability.

Anders Åström

So if you can find ways of controlling upstream variations that is the solution?

Tetsu Uesaka

Yes.