A novel approach to optimizing sheet formation on the fourdrinier

Part 1: vibrating the forming fabric vertically at or near its resonant frequency

O. Kallmes, G. Marinari, and M. Perez

Overcoming the problems created by the large-scale pulses of conventional foils, the Sheraton Roll improved the uniformity of a mill's severely flocculated market pulp.

Fiber suspensions at commercially used consistencies are in a flocculated state in the absence of microturbulence. Even when such turbulence is imparted to the slurry, the fibers return to this state almost instantaneously after the turbulence dissipates. Thus, ideally, microturbulence should be imparted continuously throughout the forming process.

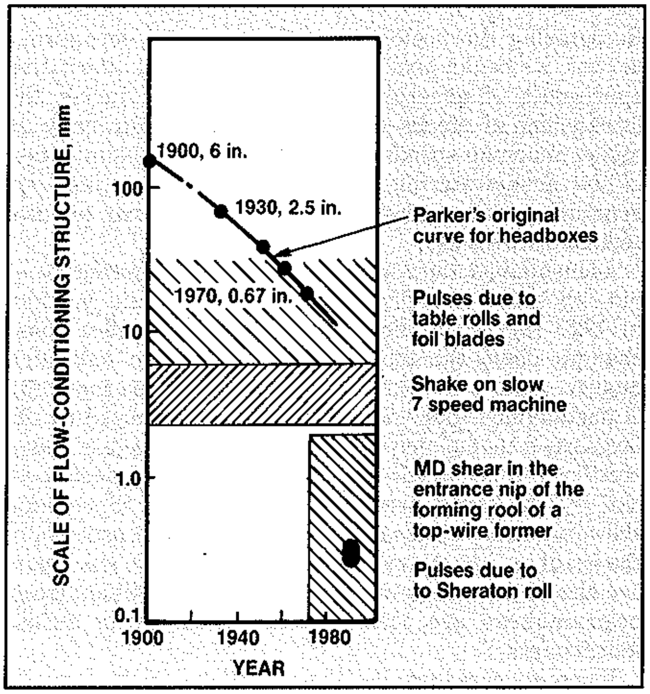
In 1968, Parker recognized that (*1*):

> ...the average floc size in a turbulent field of a fiber suspension assumes a value equivalent to or at least correlated with the average eddy size of the turbulence. In a normally decaying turbulent field, then, the average eddy size is increasing, and the average floc size increases with it. If turbulence of a sufficiently fine scale could be produced in a fiber suspension without larger-scale eddies, the primary mechanism for large scale reflocculation—i.e., large scale turbulence, would be absent...

Earlier (*2*), Parker had traced the development of headboxes in the 20th century as a steady reduction in the size or scale of their turbulence-generating structures. As shown in **Fig. 1** (*2*), the scale of these structures in headboxes has decreased steadily from about 6 in. in 1900 to 2/3 in. in 1970.

However, a headbox that delivers a well-dispersed suspension containing microturbulence is only a partial answer to producing well-formed papers. Because the dissipation of such turbulence—accompanied by reflocculation—usually starts at the forming board, comparable microturbulence should be generated and maintained throughout the sheet-forming process, but without any large-scale pulses.

1. Trends of the scale of flow conditioning in headboxes and on fourdriniers



The scale of the turbulence generated on fourdriniers can also be approximated in Fig. 1. A full-table, cross-direction (CD) shake generally has a scale less than about 1/2 in. Such a shake is highly effective in keeping stocks well-dispersed on slow machines (operating at speeds below about 400 ft/min), because it is applied every few inches of travel of the stock down the fourdrinier.

The intensity and scale of the turbulence generated by table rolls on such machines is also small and does not

Kallmes is president of M/K Systems, Inc., Danvers, Mass. 01923. Marinari is president of Steel Plant Equipment Corp., Eagleville, Pa. 19408. Perez is a professor at the Newark College of Engineering, Newark, N.J. 07102.

interfere with the quality of the papers formed. At higher machine speeds (that is, above 700-800 ft/min), however, the pressure pulses generated by table rolls become so intense that "stock jump," a form of large-scale turbulence, usually causes a deterioration in sheet quality. Figure 1 shows only that the scale of the turbulence generated by table rolls at machine speeds above 800 ft/min increases steadily as a function of machine speed.

These limitations of table rolls led to the development of the foil in the 1950s. Foils dewater stocks by exactly the same mechanism as table rolls, except that their vacuum-inducing angle is small and fixed rather than continuously increasing. Thus, at higher machine speeds, such as over 1500 ft/min, foils begin to cause the same problems as table rolls do at about 800 ft/min.

All conventional foils, whether operating freely or augmented by vacuum, generate pressure pulses that increase in geometric proportion to their dewatering rates. That is, every increase in the dewatering rate of foils is accompanied by a larger pressure pulse, which in turn creates larger flocs. It would be far more desirable to independently control (a) the rate of dewatering and (b) the generation of microturbulence without, of course, any accompanying macroturbulence.

Earlier research

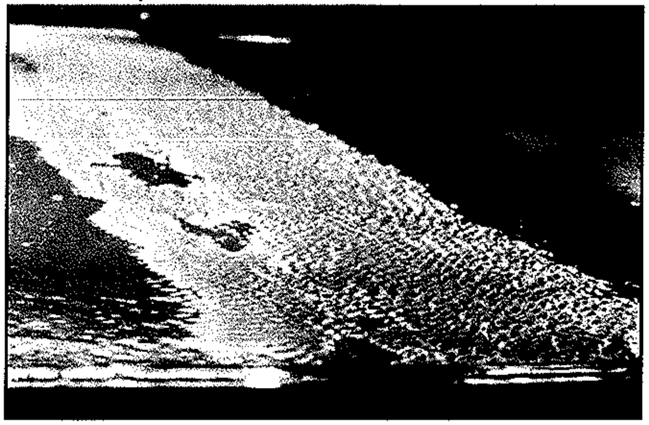
Recognizing the limitations of conventional dewatering devices, we began about ten years ago to seek alternative approaches of generating microturbulence during the dewatering of stocks on the fourdrinier, especially at higher machine speeds. We began with an examination of the nondewatering means known at that time for generating such energy. They were all found to have certain drawbacks.

As mentioned, the ancient CD shake is highly effective—but only at low machine speeds. Serrated slices, patented in 1927 (*3*), create flow ridges whose repeated phase changes down the fourdrinier can improve formation quality, up to a doubling of a sheets formation index (*4*). Unfortunately, these ridges are readily destroyed by the large-scale turbulence inherent in the discharge of many rectifier roll headboxes, especially older, overloaded ones, and by the large pressure pulses of foils. Formation showers can be utilized in a like manner downstream of the headbox, but the ridges which their needle jets create are also at the mercy of foil pulses (*5*). In addition, many papermakers are loath to mount anything across fourdriniers.

It now appears that all of these problems can be virtually overcome by two relatively new devices employed in tandem on the fourdrinier. One is a large-capacity dewatering element that does not generate any turbulence whatsoever, the Wunderfoil (*6, 7*). The second is a roll mounted under the fabric, the Sheraton Roll, which imparts fine-scale, vertical mechanical pulses (that is, a vertical shake) into the stock while causing only minimal dewatering (*8-11*).

A considerable number of both devices are now in operation on paper machines in North America and in Europe. In most cases, they have caused either modest improvements in sheet properties, or they have permitted the machines to be sped up. However, in one recent installation of a modified Sheraton Roll, this roll was discovered to have considerably greater potential than originally anticipated. Thus, it now appears that virtually all of the other Sheraton Rolls installed to date are likely to be operating under conditions that are far from optimum. In this article, we will take a close look at the theory and operation of this modified Sheraton Roll.

2. The stock just downstream of the Sheraton Roll started to bubble at a roll surface speed of about 400 ft/min.



The construction of the Sheraton Roll

The Sheraton Roll is a 5-10-in.-diameter roll mounted under a forming fabric in the same manner as a table roll. However, it differs from a table roll in that:

1. Its surface is made of a bone-hard epoxy resin embedded with glass fibers.
2. It is not truly round but is shaped rather like a gear.

The land area of its teeth in contact with the fabric is typically about 0.25 in. long circumferentially, and the tooth-to-tooth spacing, or "gap," is 0.5-1.0 in. long. The flanks of its teeth make an angle of 60° to the forming fabric, and their root is about 0.5 in. below the tops of the teeth. The teeth are not continuous in the cross direction, but they are grooved every inch or so to provide an additional escape route for white water reaching the roll.

The modified Sheraton Roll installation

Having exhausted all conventional means, a pulp mill recently decided that the Sheraton Roll offered a promising way of improving the uniformity of the mill's severely flocculated market pulp sheet. This sheet is produced from thick-walled, bleached softwood fibers. However, because of the exceptionally slow operating speed of the pulp machine, the pulses generated by a Sheraton Roll driven by the fabric would be so weak as to be ineffective. Therefore, the roll was equipped with a d.c. motor whose speed could be controlled over a wide range.

Being a somewhat experimental installation, the roll was mounted at the point on the table where it was most convenient. This point turned out to be about halfway down the forming zone, where the stock thickness had been reduced from a slice discharge of 2 in. down to about 1 in. In other words, it was installed at a point where roughly half of the sheet had been formed. Table rolls were in contact with the fabric 9 in. ahead of the Sheraton Roll and 19 in. beyond it. (Fabric-driven Sheraton Rolls located more than a few dewatering elements downstream of the forming board have not produced any improvements in sheet properties.)

At the start-up following its installation, the roll was driven at a surface speed of about 1000 ft/min because all of the other Sheraton Rolls in operation are driven by the fabric on machines running in the range of 1000–2000 ft/min. Nothing happened in the way of improvements in sheet uniformity. So the roll was sped up, and still nothing happened. What to do? The obvious next step was to slow it down.

At a roll surface speed of about 400 ft/min, the stock just downstream of the Sheraton Roll started to "bubble," an effect that peaked at 350 ft/min and virtually disappeared at about 300 ft/min (**Fig. 2**). At 350 ft/min, a significant amount of stock jump can often be observed. This massive agitation occurs despite the preforming of half of the heavy pulp sheet (over 400 g/m²!). More important, the uniformity of the sheet was dramatically improved at this roll speed; the M/K Formation Index was more than doubled.

It took little time to figure out that when the Sheraton Roll had a surface speed of 350 ft/min, the section of the forming fabric downstream of the roll and the partially formed web it supported were at their natural resonant frequency.

There are virtually no disturbances of the surface of the stock visible over fabric-driven Sheraton Rolls—and all of these are operating on much thinner layers of stock. Consequently, a Sheraton Roll running at a rotational speed that causes the fabric to vibrate at its resonant frequency introduces far more energy into the stock (perhaps ten times as much or more) than one operating at nonharmonic frequencies. Therefore, it may well be desirable in most cases not to operate Sheraton Rolls right at the resonant frequency but rather at some controlled speed close to it.

The velocity of waves induced by the Sheraton Roll

Any standard text on vibration theory (*10*), will show that the velocity of the propagation of a wave down a filamental element (such as each machine-direction strand of the fourdrinier fabric) induced by an oscillating vertical action is

$$V = (T'/\rho')^{1/2} \quad (1)$$

where

V = velocity of the wave

T' = the stress applied to the element, force/unit of cross-sectional area

ρ' = overall density.

Both terms are extremely difficult to determine for a forming fabric. However, if they are both divided by the height of the forming fabric, T' reduces to T, the tension per unit width of fabric, and ρ' reduces to ρ, the weight of the fabric per unit area, or its "basis weight." The value of ρ is always known, and T is readily measured. Then

$$V = [(T/\rho) \times g]^{1/2} \quad (2)$$

where

V = velocity, cm/s

T = tension, g/cm

ρ = fabric weight, g/cm²

g = the gravitational constant, 980 cm/s².

For a fabric under a tension of 25 lb/in. and having a basis weight of 200 g/m²,

$$V = [25 \text{ lb/in.} (454 \text{ g/lb} \div 2.54 \text{ cm/in.}) \times 980 \text{ cm/s}^2]/(0.02 \text{ g/cm}^2) = 14{,}800 \text{ cm/s} = 9000 \text{ m/min} = 30{,}000 \text{ ft/min} \quad (3)$$

Under typical fabric tensions, the vertically oscillating waves induced by a Sheraton Roll travel along the fabric at least ten times faster than the machine speed. The importance of this calculation is that it shows these waves travel fast enough—even at the highest machine speeds—that the fabric speed should not be a factor in the effectiveness of a Sheraton Roll on an upstream section of fabric.

Resonant frequency vs. other frequencies

Before proceeding, it is worthwhile to describe very briefly the difference in the behavior of a section of fabric oscillating at its resonant frequency, and at other frequencies. At resonance, the vertical motion induced by the Sheraton Roll travels undisturbed all the way down the fabric to its two points of contact with the equally-spaced preceding and following stationary surfaces. This vertical motion reaches these stationary surfaces just after the point over the Sheraton Roll arrives at its peak.

The subsequent downward movement of the point over the roll is followed by these sections of the fabric in the same way. In other words, at resonance, every point of the fabric along its lengths—between (a) the roll and (b) the two equally spaced contact points of the fabric before and after the roll—undergo the same type of vertical oscillation as the point of the fabric directly over the roll. When the free lengths of fabric between the Sheraton Roll and the next contact points with it are relatively long, i.e. over about 15 in., the amplitude of the oscillation is a maximum midway between the roll and the contact points.

On the other hand, at other frequencies, the point of the fabric directly over the roll starts down long before the vertical motion of the fabric has reached the next contact points. As a result, the vertical motion never reaches them. The greater the difference between the active frequency and the resonant one, the less of the fabric oscillates like a point over the roll, and the smaller the amount of energy introduced into the stock.

How far along a fabric under a tension of 25 pli does a wave travel during one pulse of a fabric-driven Sheraton Roll on an average 1800-ft/min machine (550 m/min)? In other words, how far does it travel at a typical nonresonant frequency?

Let us assume the roll has a diameter of 8 in. (20 cm), 29 teeth with land areas of 0.6 cm, and gaps between them of 1.60 cm. These are the dimensions of most Sheraton Rolls currently in operation. At 1800 ft/min or 900 cm/s, one tooth of the roll driven by the fabric takes

$$(1.60/2)\ \text{cm} \div 900\ \text{cm/s} = 0.00089\ \text{s} \quad (4)$$

to rise to its peak height. During this period, the wave travels both upstream and downstream a distance of

$$1.48 \times 10^4\ \text{cm/s} \times 8.9 \times 10^{-4}\ \text{s} = 13\ \text{cm} = 5\ \text{in.} \quad (5)$$

At that point in time, the fabric starts to fall again. This downward motion will start to cancel the rising wave, which therefore cannot travel much further.

The natural resonant frequency of the fabric is (*10*):

$$F_r = 1/(4\ length)\,(T\,g/\rho)^{1/2} = 1/(4\ length)\,V \quad (6)$$

where

F_r = natural resonant frequency, pulses/s or Hz

length = the distance between the Sheraton Roll and the nearest contact points of foils on either side of it.

For this example, assuming that there are foil blades 20 cm on either side of the contact point of the fabric with the roll (that is, *length* = 20 cm), the resonant frequency is:

$$F_r = (1/80) \times 1.48 \times 10^4 = 185\ \text{Hz} \quad (7)$$

When this same roll is driven by the fabric, the frequency of the pulsations, F, is calculated as follows. The surface speed of the roll is 900 cm/s, and the tooth-to-tooth spacing is 2.20 cm. Therefore, the frequency of the pulsations is

$$F = 900\ \text{cm/s} \div 2.2\ \text{cm} = 409\ \text{Hz} \quad (8)$$

which is more than twice the resonant frequency of the fabric.

Finally, the amplitude of the pulsations of the Sheraton Roll, A, is given by the following equation:

$$A = G^2/4D \quad (9)$$

where

G = the gap between the teeth

D = the roll diameter.

Equation 9 is readily derived from Euclid's Secant Theorem.

For our example,

$$A = 1.6^2\ \text{cm}^2/(4 \times 20\ \text{cm}) \times 0.032\ \text{cm} = 0.0126\ \text{in.} \quad (10)$$

This pulsation is truly "micro" in nature. However, Eq. 9 holds only for Sheraton Rolls always in contact with the fabric. It is possible to reduce the amplitude of the pulses by lowering it slightly so that its teeth contact the fabric only during a portion of their passage under it.

The parameters of Eq. 6 for the pulp machine were measured. They are given in **Table I.** Solving Eq. 6, then, for ρ and using 48 cm for *length* gives

$$\rho = (T \times g)/(4\,F_r^2\rho^2) = 376\ \text{g/m}^2 \quad (11)$$

This calculated value of ρ is a little over twice the ρ of the fabric alone. The difference, 215 g/m², is a little less than half of the weight of the pulp sheet being produced on the machine. With roughly half of the sheet formed at this point, this fit of theory and measurement is almost too good to be true. (We neglect here the viscous drag of the water on the vibrating fabric, which at least in this case appears to be negligible.)

I. Parameters measured for the pulp machine

Parameter	Units	Measured value	Comments
F_r	Hz	50	...
T	lb/in.	20	...
ρ	g/m²	161	Fabric only
$Length_1$	cm	2 × 23	To the table roll upstream
$Length_2$	cm	2 × 48	To the table roll downstream

An indication that we are dealing with a case of the resonant frequency only is that at a roll surface speed of 350 ft/min (50 Hz), only the stock over the portion of the fabric between the Sheraton Roll and the downstream table roll was bubbling (*length* = 48 cm). The 23-cm-long free section of stock ahead of it, which is at the first harmonic frequency ($2\,F_r$), was quiescent. Presumably, the heavy weight of the mat passing through this zone prevented a first harmonic type of vibration.

The number of pulses applied to the stock in passing over the section of fabric oscillating at its resonant frequency is

$$N_p = (length/S) \times F_r \quad (12)$$

where

N_p = number of pulses, pulses/s

S = machine speed, cm/s.

Substituting Eqs. 2 and 6 into Eq. 12 gives

$$N_p = V/(2S) \quad (13)$$

In other words, the number of resonant pulses applied to the stock is the ratio of the speed of propagation of the wave to the machine speed. However, it is not a function of the length of the fabric being oscillated because it does not contain the term *length*. For the 1800-ft/min machine in our example,

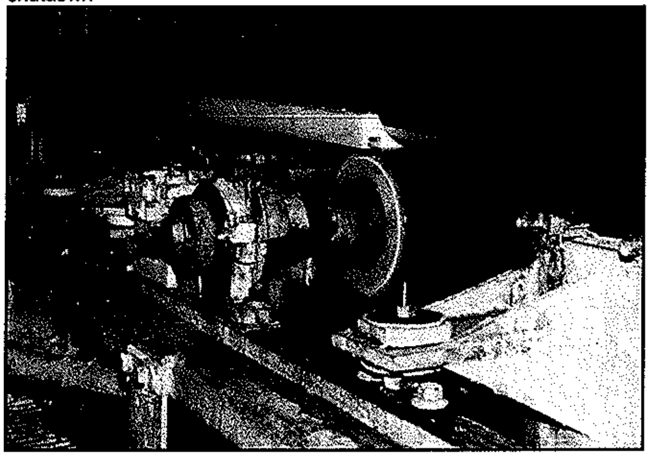
$$N_p = 14{,}800/(2 \times 900) = 8.2 \quad (14A)$$

For the 200-ft/min machine,

$$N_p = 4800/(2 \times 100) = 24 \quad (14B)$$

While the number of resonant pulses applied to the stock is independent of the length of the resonating zone, the agitation period depends strictly on the length and the

3. Sheraton Roll and Wunderfoil on a specialty machine during a shutdown



machine speed:

$$T_A = length/S \qquad (15)$$

where

T_A = agitation period for a section of fabric between the Sheraton Roll and the next foil blade, s

Again, for the example 1800-ft/min machine,

$$T_A = (40/900) = 4.4 \text{ ms} \qquad (16A)$$

On the pulp machine 200 ft/min pulp machine (with agitation only downstream of the Sheraton Roll),

$$T_A = (48/100) = 480 \text{ ms} \qquad (16B)$$

If the agitation zone ahead of the Sheraton Roll were the same length as that downstream of it, this period would be almost a full second.

Practical considerations

With the speed of the machine and the fabric tension governed primarily by other considerations, what is the optimum length that should be used in a given situation? This *length* is the only parameter governing the resonant frequency of the fabric over which the papermaker has any degree of control.

The characteristic of papermaking stocks that sets the criteria is that once fine-scale agitation ceases, fibers begin to refloc virtually instantaneously. Thus, such agitation should be imparted to the stock as continuously as possible during the formation of the sheet, when it is most needed.

Because the vibration of the fabric is terminated by contacts with solid elements, locating Sheraton Rolls between conventional foil beams is far from ideal. Agitation will cease, and reflocculation will be initiated a few inches downstream of the first foil blade on a beam. Furthermore, the time of agitation of such an arrangement is necessarily short.

When we recognized these characteristics of Sheraton Rolls, we also considered operating them in tandem with Wunderfoils, as shown in **Fig. 3**. We had been working for some time with this foil that does not generate turbulence and that has only a single contact point with the fabric upstream of six (or more) dewatering elements. We had conceived of this foil as a means of overcoming the problems created by the large-scale pulses of conventional foils. However, we had not found a generally viable and acceptable means of independently introducing fine-scale energy into the stock during formation until we came upon the Sheraton Roll. Still, the results obtained with fabric-driven Sheraton Rolls have been variable at best. It was not until after the pulp mill installation that we hit upon the concept of agitating fabrics at or near their resonant frequency.

In Part 2, we will describe (a) the principles and operation of the Wunderfoil and (b) the results obtained on paper machines operating Wunderfoils and motor-driven Sheraton Rolls in tandem.□

Literature cited

1. Parker, J. and Hergert, O., Tappi 51(10): 425(1968).
2. Parker, J., Tappi 44(4): 162A(1961).
3. Davies, D. B. and Thomas, J., U.S. Patent 1,233,096 (April 5, 1927).
4. Kallmes, O. and Perez, M., Tappi J. 65(11): 67(1982).
5. Kallmes, O., Kufferath, W., and Thorp, B., V. Punton Papermaking Raw Material, Mech., Eng. Pub. Ltd., London 1985, p. 445.
6. Kallmes, O. and Radcliffe, J., 1987 Papermakers Conference Proceedings, TAPPI PRESS, Atlanta, p. 211.
7. Kallmes, O., American Papermaker 2(11): 46(1987).
8. Ferguson, K., Pulp & Paper 62(9): 214 (1988).
9. Kallmes, O. and Marinari, G., Proceedings of the 1988 Annual Meeting, Tech. Sect., CPPA, Montreal, p. 119.
10. Kufferath, W. and Kallmes, O., Wochenblatt Fur Papier Fabrikation 116(21): 899 (1988).
11. Kufferath, W., Kallmes, O., and Steffen, H., Das Papier (10): V140 (1988).
12. Thomson, W. T., Vibration theory and application, Prentice Hall, 1965, p. 264.

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