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INSTABILITY AND THE PAPERMAKING PROCESS

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ABSTRACT

Mechanisms causing instability and change are commonplace in nature. Similar phenomena exacerbate the tasks of devising, building and maintaining systems for efficiently manufacturing paper to a tight specification and high standard of uniformity.

In the case of a machine calender stack, CD control can impart stability to an otherwise unstable system. Instability of the headbox or approach flow system can however seriously affect the MD control of basis weight. Some types of instability lie outside the reach of control, and must if possible be eliminated through improved equipment design. For this reason a good understanding of instability is necessary.

This paper considers some specific examples of unstable behaviour, including eddy and vortex formation, waves and other amplification mechanisms on Fourdrinier wires, corrugation growth, uneven wear, self-excited vibration, and thermal deformation affecting calender stacks.

INTRODUCTION

Instability is a characteristic of the natural world. Only by the use of very carefully designed equipment is it possible to approach the Newtonian ideal of steady motion, and only then for rigid bodies and viscous fluids. Whenever energy is available, in the form of radiation, thermal energy, kinetic energy, or in some other form, it sooner or later interacts with matter, mechanically, chemically, electromagnetically, or at the atomic level. It tends to be degraded stepwise, seldom if ever being totally converted to low grade heat in a single step. Heat may cause expansion, convection, movement, evaporation or distillation. Motion results in vibration and noise; solid friction can generate electricity as well as heat. Metals are fatigued, solids are eroded. Plane surfaces are seldom found in nature but, curiously, randomness is not the rule. Substances are segregated as well as blended, and regularities occur spontaneously both in fluid flow and in the deposition of materials.

The achievement of science has been to discover order in chaos. Engineers and technologists however must master such difficulties, build stable structures, make artefacts with precisely defined and stable surfaces, maintain steady motion with a minimum dissipation of energy, transform energy efficiently from one form to another, and uniformly mix dissimilar fluids or particulate materials. Every new process and every modification raises questions about stability. The penalty for an incomplete understanding of all of the phenomena that may be called into play ranges from less than ideal performance to catastrophe. While events such as the breaking of the Tacoma bridge receive thorough and detailed study, persistent but less spectacular problems may escape systematic study.

The aim of this paper is to consider some of the effects of instability on the manufacture and quality of paper. The discussion is based on the results of mill investigations aimed at the solution of particular problems. Subsequent laboratory work and scientific study were limited to understanding the underlying mechanisms well enough to permit a solution to be recommended. Through the references the reader is directed towards reviews and text books, as much as to original works, to allow specific points to be persued in more general terms. Pippard (1) provides an introduction to the physical theory of instability and chaos.

THE NON-UNIFORMITY OF PAPER

It is convenient to distinguish between MD, CD and residual variation within the web. These are usually defined by the statistical technique known as two way variance analysis, which provides a convenient yardstick for the measurement of non-uniformity. As a result, MD variation is confined to variations in the form of bars parallel to the cross direction. Variations in the form of oblique bars are automatically assigned to residual variation which may therefore include some effects from pulsations, vibration, and even short term consistency variation. It is preferable to define MD variation such that it includes all variations that extend across the width of the machine, whether parallel or oblique and regardless of whether their pitch is uniform or random. Such variations would all originate outside the forming zone. Residual variation would then refer solely to localised variations which extend only for a limited distance across the machine.

As seen by an on-machine gauge the frequencies excited by MD and residual weight variation in a web moving at 600 m/min extend from at least 30kHz down to 0.3mHz, a range of eight decades. Only those corresponding to flocculation and to process control frequencies, perhaps four decades in all, have been the subject of persistent study. In spectral terms, the variations have approximately constant power per decade, such that the coefficient of variation of basis weight per decade of frequency lies roughly in the range 1.2 - 1.5 per cent rms. This concept may be useful to control engineers although it falsely suggests that the variations are unstructured.

Many different causes of MD and of random weight variation have been identified. These include flocculation, disturbances in the forming zone, amplification of waves on the Fourdrinier wire, eddies in the headbox and pipework, vibration, pulsation, poor design of the approach flow system, and faults in control equipment. Other problems, especially corrugation growth, cause line load variation at press and calender nips with consequent variation of moisture content and caliper. Taken together these effects cause variation in density and smoothness, and a disproportionate loss of paper strength (2). They also cause errors in the laboratory evaluation of paper properties and thus add to the difficulties of the control of stock quality and refining.

THE EFFECTS OF PROCESS NOISE ON CONTROL

This topic was reviewed just 20 years ago by Brewster & Bjerring who stressed the importance of eliminating process noise (3). The effects of process noise on control are particularly serious in the presence of a transport lag. Although efficient methods for control in the presence of a time lag (4) are now in common use, they do not circumvent the problem. In theory, even in the absence of process noise, if process variations are restricted to some band of frequencies of width $\underline{b}$, then regardless of the mean frequency of the band, useful control is possible only if the time lag is less than $1/2\underline{b}$. This may be demonstrated by the use of Cornu's spiral. Since the frequency content of disturbances to be controlled usually extends to zero, a pure transport lag $\underline{L}$ restricts useful control to variations having no frequencies greater than $1/2\underline{L}$. In practice, this cut-off frequency depends on the frequency content of the process variations. It falls off rapidly if significant components of higher frequency are present. Filters are of little value for eliminating such components because they introduce an additional time lag. For example, to attenuate components having frequencies greater than $\underline{f}_m$, using a moving average filter, the variations must be processed over a time span of about $2/\underline{f}_m$, and the filter lag $\underline{L}_f$ is therefore $1/\underline{f}_m$. If $\underline{f}_m$ were twice the cut-off frequency $1/2\underline{L}$, then $\underline{L}_f$ would be equal to $\underline{L}$. It is worth reflecting on the fact that the low frequency variations associated with white noise in a process cannot be eliminated by control, even if filtering is applied, because white noise is essentially unpredictable. For good regulation of basis weight, it is recommended (3) that wet end disturbances should be minimised by careful attention to headbox and consistency control.

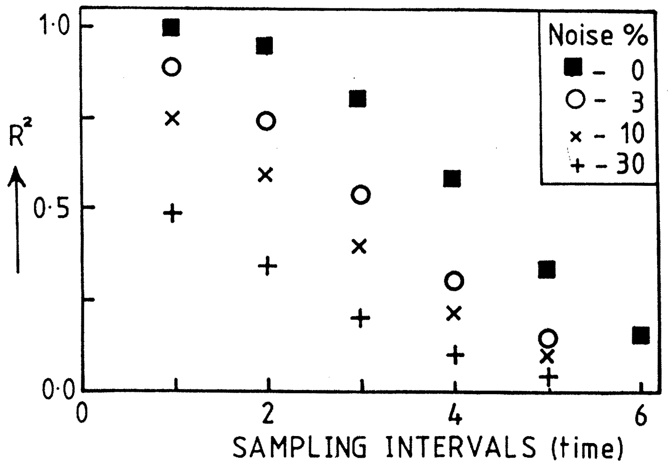


Fig. 1 The effect of process noise on the simulated prediction of basis weight variation. The noise is given as a percentage of the total variance.

The essential problem in basis weight control is to forecast the weight that corresponds to the mixed stock currently being diluted with backwater. To illustrate the effect of process noise, calculations were made based on a hypothetical basis weight signal with a power spectrum corresponding to the Gauss function.

$$\phi(f) = \exp(-\pi f^2) \quad (1)$$

Such a signal would contain little noise above some limiting frequency, arbitrarily chosen here as f = 1. It was assumed that values of this signal, x_i, would be sampled at regular intervals T. In order to predict its value k intervals ahead, the autocorrelation function was found and from it, by multiple regression, expressions for x_{i+k} were obtained in the form:

$$x_{i+k} = b_1 x_i + b_2 x_{i-1} + b_3 x_{i-2} + \ldots \quad (2)$$

At the same time, corresponding values of R^2, the square of the multiple correlation coefficient, were computed. These gave the proportion of the variance of weight variation that could be predicted and thus, in theory, eliminated. The calculation was repeated using autocorrelation functions modified by the addition of different proportions of high frequency noise. The sampling interval T was taken throughout as one eighth of the period corresponding to the limiting frequency. The results are shown in Fig. 1.

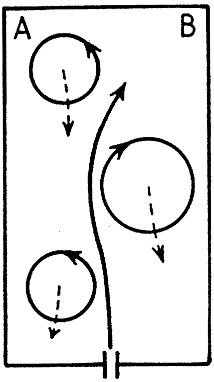
Taking R^2 = 0.5 as the limit for useful control, it appears that, with no added noise, predictions could be made across a lag corresponding to half the period of the limiting frequency of the signal. Ten per cent of added noise halved this cut off frequency, while thirty per cent decreased it roughly fivefold. This example represents only a snapshot of the situation before control is applied. Control action would remove the lowest frequencies efficiently, leaving those nearer the cut off frequency only partly attenuated. Variation would be reduced to a level dictated, among other things, by the noise level in the region of the cut off frequency.

Finally, in this section, the effect of instability of the CD basis weight profile should be noted. Both CD and MD variations are estimated from the output of a scanning gauge and the accuracy with which the MD variation can be predicted is directly dependant on the CD profile stability and the residual variation. Automatic control of the slice is capable of correcting, in the longer term, for the effects of CD instability, but it can do nothing to eliminate its adverse effects on the estimation of the MD variation.

INSTABILITY OF THE WET-END CAUSED BY EDDIES AND VORTICES

The basic rules to be followed in the design of the short circulation loop are now well established (5,6). See Veyre (7) for a comprehensive account of wet end problems and their effects on MD weight variation. A common cause of severe medium term weight variation is unsatisfactory mixing of the backwater with the mixed stock and recirculated thin stock. Mixing must be rapid and complete, and carried out in the smallest possible volume with no dead space for accumulation of fibre. If any stock is allowed to enter the silo, surprisingly slow weight variations may occur. The following observation suggests an explanation.

Figure (2) shows an unstable pattern of three eddies in a shallow chemical mixing tank, caused by liquid pumped in through the centre of the shorter side. These eddies slowly move towards this end of the tank while others form, as suggested by the broken arrows. Despite high fluid velocities, the time for a complete cycle of this instability is similar to the residence time of the liquid in the tank. Similarly, the slow shedding of eddies from a side branch following a bend in a thick stock main is believed to have caused headbox pressure variations with a two second period (Fig. 3). The variations which were traced to this point in the pipe vanished when the side branch was resited.



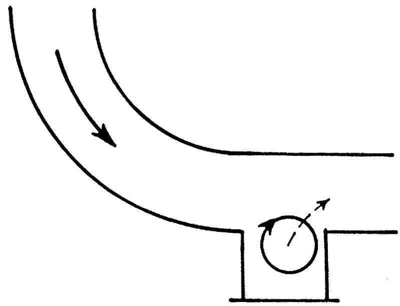


Fig. 2 Plan view of a mixing tank showing a flow pattern varying slowly with time. Eddies form alternatively at A and B and slowly move towards the inlet near which they vanish.

Fig. 3 Eddies released cyclically from a recess following a pipe bend.

Slice Flow Instability

Slice flow instability has been discussed by a number of authors. Howe & Cosgrove provide a comprehensive account (8,9), and distinguish four main categories of disturbance (9).

1. Stable Wakes from fixed obstructions in the headbox such as evener fins.

2. Unstable Turbulent Wakes with no CD periodicity, from transverse rods close to the slice.

3. Unstable Wakes from perforated rolls.

4. Gross Instability due to large scale unevenness of the flow within the headbox body.

These authors also describe "apparently stable wakes (ASW's) which were unstable in time, tending to move from point to point across the width of the (slice) jet". They noted that "This transverse instability was much more severe in its effect on the paper formation than turbulent wakes". They showed this effect could be suppressed by placing a transverse rod in a converging slice. Their ASW's resembled those that can be seen, for example, in the jet from a Converflo slice at a CD pitch of about 12mm. While no certain explanation can be given, there are indications that they may be linked with vortices similar to those studied by Taylor (10).

Taylor-Couette vortices develop in fluid contained in the gap between concentric cylinders rotating at different speeds. They take the form of uniformly spaced spirals, each completely encircling the inner cylinder. Alternate vortices rotate in opposite directions. Such vortices were studies by Lee (11) in relation to a pressure forming inlet on a wadding machine. The vortices formed around the fully immersed forming roll and caused stable streaks in the product. Lee also referred to work on similar spiral motions - (Taylor-Gortler vortices) (12) - in flow around concave surfaces, and at bends in narrow rectangular channels.

In recent experiments on the behaviour of "condensate" in a transparent 150mm diameter model drying cylinder, pigment was added to make the liquid visible. At speeds of about 5 revolutions per second the liquid encircled the inside of the cylinder and the pigment was deposited in rings of roughly uniform spacing. For liquid films 0.7 - 1.5mm thick the average spacing of the rings was 1.4 - 2.0 times the film thickness. For a 2mm film, more closely spaced rings also appeared. The pitch of the rings was presumably double the spacing of the individual vortices (Fig. 4). The vortices formed as a result of relative motion between liquid and cylinder through the action of gravity.

Finally, Prandtl (13), in discussing the differences between heat and momentum transfer in turbulent flow, remarked that "in turbulence due to friction at a boundary, eddies with their axis parallel to the flow apparently predominate, whereas in free turbulence eddies with their axis at right angles to the flow predominate". Thus it seems possible that spiral eddies aligned in the flow direction, clinging to the walls of the flow channel before the slice, may account for an important type of slice jet instability.

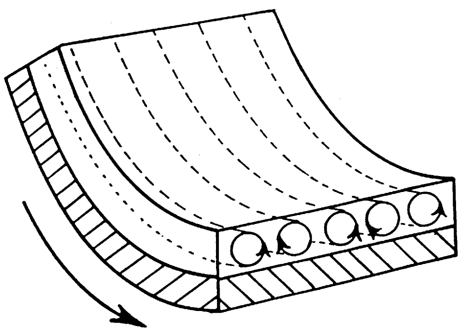


Fig. 4 The suggested form of spiral eddies in the "condensate" layer in a rotating model drying cylinder.

AMPLIFICATION OF DISTURBANCES ON THE FOURDRINIER WIRE

This has been studied in some detail in connection with wakes and spouting and also wet end barring. It was considered by Mardon & Truman (14) that vertical acceleration of the wire, causing "Taylor instability" (15), was responsible for the initial growth of spouts, while backflow on impingement of the slice jet with the wire contributed to wakes on the wire (16). Parker (17), showed that the development of waves in the stock on the Fourdrinier could explain how wet end barring could be caused by minor stock velocity variations at the slice, and later a more elaborate explanation was given by Moen (18). (For a comprehensive intrcduction to waves in fluids, see Lighthill (19)).

Recently, a further mechanism causing the amplification of depth variations in shallow liquids has been noted. The phenomenon can be demonstrated by placing a shallow tray on a table, adding coloured water to it to a depth of about 0.8mm, and then moving the tray to and fro horizontally with an amplitude of about 25mm and a frequency of 2Hz. The water will pile up into irregular bars, leaving other areas relatively dry. This "shuffle" effect can be explained by considering the horizontal movement of the liquid relative to the tray. Very shallow water will tend to follow the tray, because its inertia is low relative to the friction drag. Deeper water will, in contrast, remain almost stationary while the tray moves beneath it (Fig. 5). For best results with the tray, the amount of water should be adjusted to give 50 per cent relative motion.

Consider the situation illustrated in Fig. (6), when the direction of acceleration is from the shallow liquid A to the deeper liquid B. The liquid at A will move with the tray until it impinges on the stationary liquid at B. It will then decelerate, its depth will increase, and a force will be exerted on B proportional to its rate change of momentum. When the acceleration is reversed, for the second half cycle of the oscillation, A will retreat from B, the momentum force exerted by A during the first half cycle will vanish, and B will flow back into A.

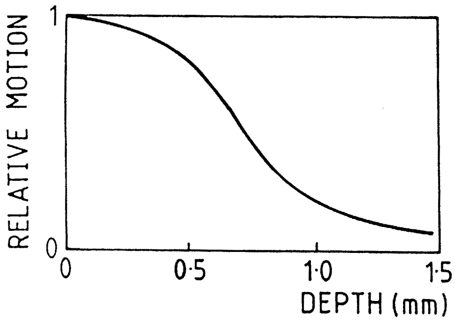


Fig. 5 Suggested amplitude of movement of shallow water on a horizontal oscillating tray, relative to the movement of the tray.

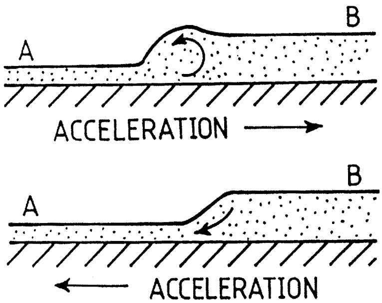


Fig. 6 The boundary between shallow and deeper liquid on a horizontally oscillating tray.

An equilibrium will be achieved such that the momentum force of A acting for the half cycle will balance the pressure force of B acting over the whole cycle. This situation resembles that of shake in a Fourdrinier. Although formation is improved it is possible that CD non-uniformity will be increased. A similar argument can be applied to stock initially moving steadily relative to the wire. Thicker stock will overtake shallow, because of the effect of drag, and variations in depth will be amplified. This effect can be clearly seen on a Fourdrinier wire during start up when the efflux ratio is very different from unity. Whenever the stock and wire speeds differ some amplification of its depth variations must be expected.

CORRUGATION GROWTH

This is a widespread problem affecting dirt roads, railway rails, abrasive grinding wheels, rollers used in steel and paper manufacture, and occasionally, the rings of anti-friction bearings. In paper mills it occurs on press rolls and felts, on reels in winders, and on both chilled iron and soft covered calender rolls. Corrugations may develop if two conditions are satisfied:

1. The surfaces in rolling contact are subject to wear, or in general, they are affected in such a way that they slowly expand or contract locally in a radial direction in response to local variations in nip load synchronised with the roll rotation.

2. Either the rolling system itself forms a resonant system, or it is mechanically coupled to such a system, such that vibration can be excited by irregularities of the rolling surfaces.

The development of corrugations on calender rolls was studied by the author and the results were published in 1965 (20). A theory was developed which was in agreement with the observations. Among other things it was predicted, - and confirmed, - that corrugations caused by wear would migrate around the surface of a roll in a direction opposite to that of its rotation. Similar observations were made by Thompson and others (21), in connection with lobe growth on abrasive grinding wheels. The theory was recently found to explain corrugation growth on a tissue mill pressure roll as a result of localised thermal expansion, rather than wear. A brief account of the theory now follows.

Consider a pair of rolls as shown in Fig 7a. The lower roll is in rigid bearings, while the upper roll is loaded against it. The material passing through the nip is assumed to act as a spring, and the lower roll surface is subject to wear. Dynamically, the system is as in Fig. (7b). The equation of motion of the mass m is:

$$m\ddot{y} + c(\dot{y}-\dot{x}) + k(y-x) = 0 \tag{3}$$

Fig. 7 A two roll stack (or wet press) and its dynamic equivalent.

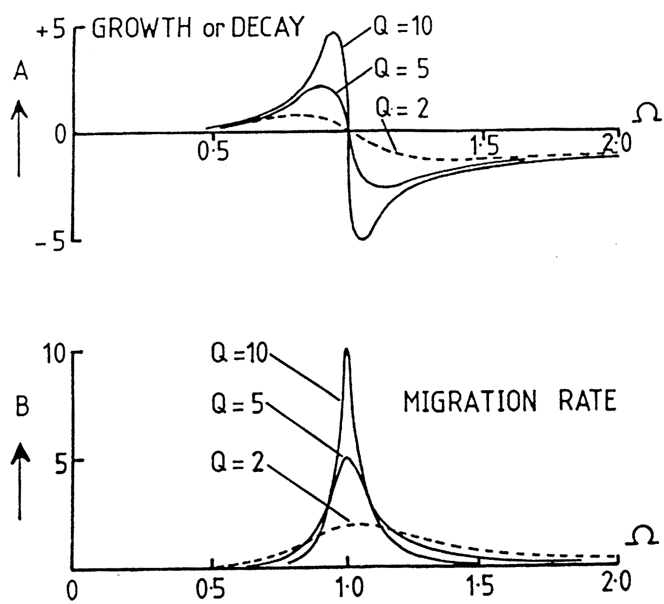


Fig. 8 The coefficients determining corrugation development plotted against dimensionless frequency.

Here, x is the displacement of the surface of the bottom roll at the nip caused by variations in its radius, while y is the displacement of the top roll. This equation may be solved for the variation in the "gap" z between the rolls, assuming initially that

$$x = \sin(\omega t) \tag{4}$$

Defining

$$z = (y - x) \tag{5}$$

$$\Omega = \omega/\omega_n \tag{6}$$

$$\omega_n = (k/m)^{\frac{1}{2}} \tag{7}$$

and

$$Q = k/c\,\omega_n \tag{8}$$

the following result is obtained:

$$z = A \sin(\omega t) - B \cos(\omega t) \tag{9}$$

Where

$$A = \frac{\Omega^2 (1-\Omega^2)}{(1-\Omega^2)^2 + \Omega^2/Q^2} \tag{10}$$

$$B = \frac{\Omega^3/Q}{(1-\Omega^2)^2 + \Omega^2/Q^2} \tag{11}$$

Coefficient A determines the variation in the gap in phase with the corrugations on the roll face. If A were positive, then the gap would be least when the trough of a corrugation was passing through the nip. Since the rate of wear of the roll face increases as the gap decreases, corrugation growth would therefore occur. Conversely, if A were negative the corrugations would decay. The plot of A in Fig. (8) thus shows the dependence of growth on frequency. Similarly, the positive values of B indicate that wear will always to some extent be concentrated on the sides of the corrugations facing the direction of motion, thus explaining their migration around the roll face.

If $\underline{W}$ is the change in the mean rate of wear per unit change in distance between the rolls, measured over many revolutions, at steady speed, then over such a time span $\underline{T}$ the amplitude of the corrugations will change according to the equation:

$$\frac{1}{x} \cdot \frac{dx}{dT} = WZ \qquad (12)$$

Where the complex quantity $\underline{Z}$ is the ratio $\underline{z/x}$. Thus the amplitude of the corrugations with change from a_1 to a_2 as follows:

$$a_2/a_1 = \exp\ (WAT) \qquad (13)$$

while their position on the roll face will change such that they lag by angle Ψ relative to their initial position, according to the equation

$$\Psi = WBT \qquad (14)$$

So far it has been assumed that corrugations of only one wavelength are present. In practice, the cross section of any roll, however well ground, is slightly irregular. The variation in radius around the circumference can be considered as the summation of sets of corrugations having 1,2.....etc., cycles per revolution of the roll. Under steady operating conditions each set will develop as dictated by equations (13) and (14). Thus the shape of the roll will gradually change, and the corrugations associated with the highest possible value of $\underline{A}$ will become dominant.

Corrugations caused by thermal expansion

Corrugations may also develop because of thermal expansion. Consider a rubber covered roll, running against a Yankee cylinder, with a felt or mesh screen passing through the nip. Suppose that the roll is cooled internally but its cover receives heat either from the screen or as a result of mechanical hysteresis. In the absence of vibration if a new roll is put into use its cover will come to a steady working temperature and its radius will be reasonably uniform. Should the temperature of some part of the cover be raised by a temporary input of heat then we may suppose it would return exponentially to the steady temperature as dictated by some time constant $\underline{k}$. The change in its shape caused by thermal expansion would similarly decay.

Suppose now that a sinusoidal variation in temperature is somehow induced around the roll circumference. Thermal expansion will cause a corresponding variation $\underline{x}$ in the roll shape, and because of vibration the gap between the rolls will vary. This in turn will cause local changes in the heat input to the cover, such that the roll radius changes locally at a rate given by $-\underline{hz}$ where the coefficient $\underline{h}$ depends on the rate of change of heat input with gap and on the roll cover characteristics. The sign is negative because increase in gap decreases the expansion. The rate of growth of the thermal corrugations will be given by:

$$\frac{1}{x}\cdot\frac{dx}{dT} = -(hZ + k) \qquad (15)$$

so that in this case:

$$a_2/a_1 = \exp -(hA + k) \qquad (16)$$

and

$$\Psi = -\ hBT \qquad (17)$$

For growth to occur, $\underline{A}$ must now be negative, and $-\underline{hA}$ must exceed $\underline{k}$. Growth will therefore occur just above the resonance frequency, and only if the amplification factor $\underline{Q}$ (equation 6) is sufficiently high. Thus it may prove possible to eliminate completely such vibration by adding dampers to the roll bearings. Equation (15) shows that the corrugations will migrate in the direction of rotation of the rolls, and thus in the opposite sense to corrugations caused by wear. The values of $\underline{k}$ and $\underline{h}$ are such that thermal corrugations develop in minutes, rather than days, as in the case of wear.

REGENERATIVE FEED BACK AND CALENDER STACK VIBRATION

Regenerative feedback is the prime cause of calender barring on high speed newsprint machines. Calender stacks behave as mass spring systems with several modes of vibration in the vertical direction. Vibration is found to occur even if no corrugated rolls are present. Also, despite suggestions to the contrary, no decisive evidence has been published demonstrating that calender barring is caused by cyclic weight variation. The most probable explanation of the phenomenon is that the vibration is maintained by thickness variations impressed into the web near the top of the stack by the vibration itself (22). If these variations pass through subsequent nips such that the nip pressure is increased as the rolls move apart, this could maintain the vibration indefinitely. See Fig. 9. This explanation is strongly supported by the way in which the frequency of vibration changes discretely as line load, moisture level or machine speed are altered.

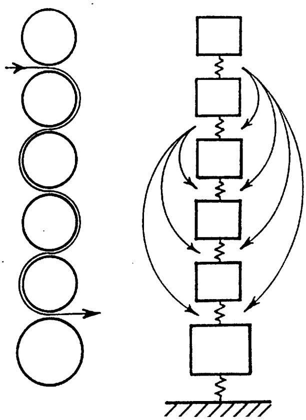


Fig. 9 A machine stack and its simplified dynamic model showing some of the feedback paths provided by the web.

As in the case of thermal corrugations, a certain rate of energy input is required to replace that which is absorbed by mechanical damping. If it falls below this limit, the vibration ceases. One practical solution to the problem is to use rolls with carefully calculated diameters and offsets so as to minimise the feedback for each mode of vibration. Alternatively, the introduction of mechanical damping by careful roll design provides, at the least, a potential solution (23).

DRYER SECTION VIBRATION

Problems of severe machine direction vibration of entire dryer sections of fast machines have occasionally been reported. Such problems occur when a dryer section is supported by columns from the basement and isolated from the machine floor. The vibration occurs at a frequency which is (a) about five per cent less than that of the drying cylinder rotation frequency and also (b) slightly less than the natural frequency of the dryer section on its columns. An explanation is suggested by the appearance of the problem some ten minutes after the sheet is put through the dryers, and its disappearance a similar time after a web break. All the circumstances point to condensate as a cause. To prove the point, a transparent 150mm diameter model cylinder was mounted on leaf springs, (Fig. 10a.) such that its resonance frequency was about 10Hz and its rotation speed could be varied. It vibrated in the same way as a dryer section if water was added to form a ring of 1mm average depth. When the vibration occurred the water formed a "slug" as shown in Fig. (10b). This would exert a horizontal force on the cylinder, roughly in phase with the vibration velocity and thus maintain the vibration.

The slug does work and would slow down unless supplied with energy. It rotates more slowly than the drying cylinder and is driven by it by friction. The slug remains intact, and does not collapse into a uniform ring of condensate, because a thin layer of condensate is picked up from its tail, accelerated by the drag of the cylinder wall, and thrown against its face.

This mechanism resembles that of the "shuffle effect" noted in relation to Fourdrinier wires. The vibration in the model cylinder developed spontaneously when the cylinder rotation frequency was somewhat higher than the resonance frequency. For a dryer section it is probably initiated by transient vibration causing slugs to form in one or two cylinders; the vibration from these then causes slugs to form in other cylinders.

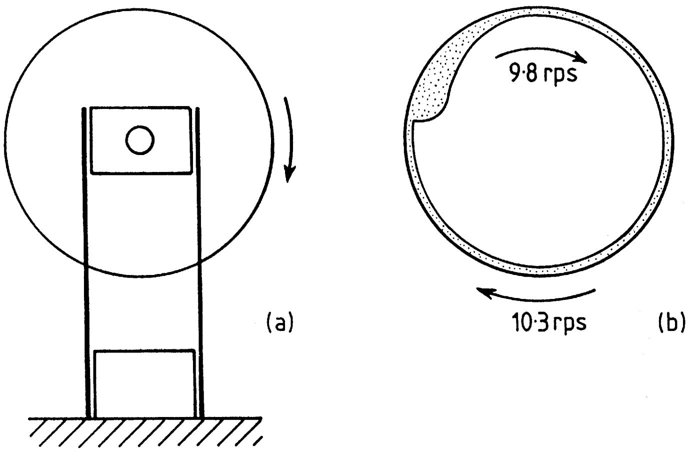


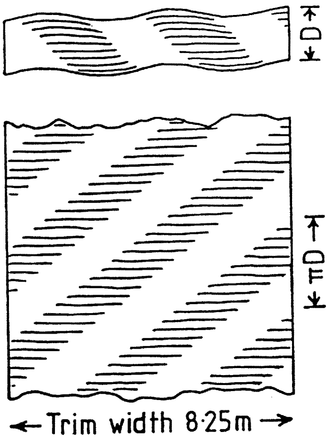
Fig. 10 A well balanced model of a drying cylinder supported on leaf springs so that it has a horizontal resonance at 10.0Hz. When driven at 10.3 revolutions per second it vibrates strongly at 9.8Hz because of imbalance caused by a slug of condensate.

THERMAL INSTABILITY OF CALENDER ROLLS

In recent years some remarkable examples of instability have been noted in two roll calender stacks. These have been characterised by strong MD variation of caliper or roughness, synchronised with the rotation of one or other of the rolls. Vibration is absent. Careful examination of the web reveals a diagonal pattern of variation (Fig. 11), and it can be shown that the affected roll is deformed into a helix with two full turns across the width of the web.

One example, which was studied in some detail, concerned an 8.25 metre wide machine, making 60 gsm paper at 700 m/min. The top chilled iron roll was 900 mm in diameter with a small bore through which hot water was circulated. The bottom roll was a swimming roll; this was not involved. When a reground top roll was put into use, the paper was at first uniform, but a diagonal pattern slowly developed in the course of 1-2 weeks. The ingoing paper thickness was 94 µm, and the calendered paper caliper ranged from 63 - 93 µm, mainly as dictated by the pattern. A check when the machine was shut showed the helix on the top roll was deep enough to allow a 38 µm feeler gauge to be passed into the nip at certain points. The temperature variation around the top roll was at least 2 deg. C.

The problem was clearly the result of uneven heat transfer from the web to the roll; careful checks ruled out mechanical defects. The web was 10 deg. C warmer than the roll. It was reasonable to suppose that heat transfer from web to roll would vary locally with nip pressure. Rough calculations showed that a 4 deg. C temperature difference across a diameter was necessary to account for the observed roll shape. They also confirmed that the heat flow from the web to the roll would be capable of sustaining this temperature variation. Such results were sufficient to allow solutions to be suggested, but the problem cannot be left without an attempt to explain why the helix contained 2.2 turns.



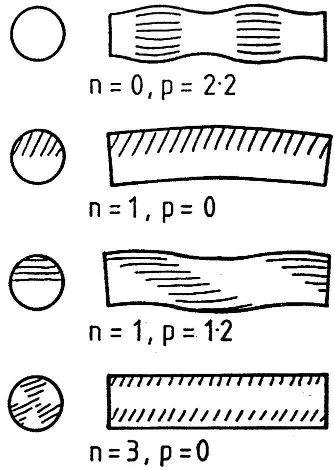


Fig. 11 Deformation of a calender roll caused by the thermal spiral n = 1, p - 2.2, and its effect on the paper web. Shaded areas are hotter or smoother than elsewhere.

Fig. 12 Examples of different patterns of roll deformation.

It is assumed in the first place that the affected roll was approximately cylindrical when at uniform temperature. During use slight irregularities in its shape would cause corresponding variations in heat transfer and thus local variation of temperature within the roll. Following Fourier, these irregularities may be considered as the resultant of many components, each representing a spiral having $\underline{n}$ threads per revolution of the roll and making $\underline{p}$ turns across the width of the web. See Fig. 12. The term $\underline{n}$ must be an integer but $\underline{p}$ may have any value.

The case $p = 0$ corresponds to the roll corrugations discussed previously. For $p = 0$ and $n > 1$, any section through the roll would exhibit symetrically arranged lobes, and the roll axis would remain straight, If however, $n = 1$ thermal expansion would cause the roll axis to bend, so that for $p = 0$, the roll would become banana-shaped, while for $p \neq 0$ the result would be a helix.

With reference to the two roll stacks, only for $|p| > 2$ would the two rolls always make contact at two or more points and be capable of rolling without rocking. For $|p| < 2$ one roll could rock against the other and their contact points would be ill defined. For a given temperature difference across the roll diameter, the smaller $|p|$, the larger would be the distance between the contact points, and the greater would be the variation in the gap at the nip, the nip pressure, and the heat transfer coefficient. Also, as $|p|$ decreased, the heat flux within the roll necessary to maintain a given temperature variation would decrease. Thus the smaller $|p|$, the more rapidly would a thermal helix tend to develop and also, the greater would be its effect on the paper. However, given the further requirement $|p| > 2$ for well defined rolling contact, the observed value 2.2 is consistent with expectations.

A reason for multi-roll stack instability

The case $n = 0$ corresponds to simple temperature variation along the length of the roll, with uniform temperatures over any cross section, and no distortion of the roll axis. As we have seen, the tendencies of different types of deformation to occur can be estimated by comparing the temperature gradients within the rolls, the heat flows required to maintain them, and the relative variations in roll shape caused by a given range of temperature variation. Comparison of the case ($n = 0$, $p = 2.2$) with ($n = 1$, $p = 2.2$) (see Figs. 11 and 12) showed that temper- ature variation along the roll would develop faster than the corresponding spiral, and would affect the paper more strongly. It might also develop under conditions for which the heat transfer coefficient was less sensitive to line load.

The two roll stack in the example was fitted with cross direction caliper control, so that the effect of temperature gradients along the roll was inhibited. The above considerations do, however, point to the occurrence of thermal instability in traditional multi-roll machine calenders, and may explain why constant adjustment is necessary to build a uniform reel in the absence of a caliper control system.

CONCLUSIONS

Instability has been shown to occur in different forms at many points throughout the papermaking process. It may cause vibration, unsteady flow, and uneven wear or deformation both of critical surfaces and machine clothing, thus increasing maintenance costs. Unless carefully controlled its effect is also to increase non-uniformity by introducing both regular and irregular variations into the product.

New forms of instability constantly become apparent as machine speeds and line loads are increased, equipment designs are changed, and higher quality standards are sought. Although some types of instability may readily be eliminated, others seem inherent in particular processes and are less easily dealt with. Such intractable problems may not be fully overcome until their significance is recognised, their causes are understood and such knowledge is applied to the design of new equipment.

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Transcription of Discussion

INSTABILITY AND THE PAPERMAKING PROCESS

J. R. Parker

M.I. MacLaurin

This is a request rather than a question. Would it be possible to write up an account of wave motion on the wire to be written up for the proceedings?

Dr.J.R. Parker (Written response)

I would be glad to do that. (Prepared contribution at the end of these discussions)

Dr. J.L. Brander   Wiggins Teape R & D Ltd

I have two questions, perhaps one of them is fairly trivial. I think that your shuffle effect and perhaps most examples of wave motion in the outside world are associated with friction, I have in mind road deformation for example. Would you say that calendering barring could be put in the same category i.e that it comes from the friction between the paper and the rolls?

Dr. J.R.Parker

Friction is not the cause of this type of barring. The wear responsible for corrugation growth on calender rolls was the result of the crushing of the grit in the web. The greater the line load the greater would be both this crushing action and the rate of wear of the roll face.

Dr.J.L.Brander

My second point was how did you cure that problem? Did you fit dampers and if so what sort?

Dr. J.R. Parker

One solution is to remove the source of wear i.e. the grit, using stock cleaners. Also, it helps to grind the rolls as carefully as possible and check them with a curvature gauge that deviations from circular form likely to initiate corrugation growth are little more than a micron in amplitude.

Dampers can only normally be installed on loading arms or bearing housings, so they are only effective if the rolls are sufficiently stiff to ensure they are effective across the full width of the machine. They decrease the variation and so reduce the nip pressure variation causing corrugation growth. Thus, the development of corrugations caused by wear can be significantly decreased but not completely eliminated.

In the case of the thermal corrugations, if the damping can be increased above some critical level this problem can be eliminated completely. This was successful in the case of a tissue machine pressure roll; roll life was also increased because corrugation growth caused by wear was inhibited.

Dr. J.D.Peel

I would like to return to this corrugating problem too. We have had a similar problem to your case with soft calendering recently. You describe the phenomenon of thermal corrugations forming. I am wondering if it is possible to get it in other circumstances, as when hot paper from a coater drier is running into a soft calender nip? Might that be another example of thermal corrugations starting and then it may combine with wear?

Dr.J.R. Parker

Yes I think thermal corrugations may well form under those conditions, but on reflection I must add that they would be unlikely to cause corrugations through uneven wear. When thermal corrugations are on the point of forming they can lock onto pre-existing corrugations caused by wear, thus decreasing the overall amplitude of vibration. Normally, however, the two types of corrugation behave independently, migrating in opposite directions around the roll face and riding over each other.

Dr.J.E. Luce International Paper

I would like to address the corrugations that you saw on the inside of the drum and also the spouting of ridges on top of the table.

One of the great geniuses of Stanley Mason as a teacher was that he avoided teaching as far as possible and let you work things out for yourself. Here is the experiment that you should perform which might give some insight into the mechanism behind the ridges. Take a coffee tray but do not use coffee because this is messy. Pour in between 1/2 and 1 cm of water. Level the tray and then accelerate it downwards as quickly as you can, and watch what happens. Then think of what forces are involved.There are no Taylor vortices because there is no rotation. I think that you will very rapidly come up with the explanation for the ridges inside the rotating cylinder and the spouting on the papermachine table.

Dr. J.R.Parker

On reflection I feel I must correct some misapprehensions evident from your question.

Firstly. I saw evidence of vortices, not surface corrugations, in the water rimming inside the rotating drum. We made these visible, in recent experiments, by adding "natural pearl essence", a pigment with plate-like particles, to the water. The vortices were least obvious near the lowest point of the drum and most distinct on the ascending side, near the top. Because of the effects of gravity and friction, the velocity of the fluid at this point inside the drum would have been close to its minimum value, and significantly less than that of the cylinder wall.

According to the criterion suggested by Lord Raleigh and extended by G.I. Taylor, if the angular velocity of the fluid is less than that of the cylinder wall the flow should be stable and no vortices should form. If so, the vortices I observed were caused by some mechanism other than that studied by Taylor. The vortices I saw were quite distinct from those observed by Debler and Yih (24) in a liquid rimming within a cylinder that is rapidly decelerated. Although they may effect the slice discharge, I am not convinced that they contribute to the subsequent amplification of ridges on the wire table or to spouting.

Secondly, concerning ridges and spouting, an experiment by Yih and Lin (25) in which a tray of water was allowed to fall freely onto a rubber pad demonstrated very clearly that strong growth of small initial disturbances to the water surface occurred as a result of this sudden deceleration. Little growth occurred during the period of free fall.

Dr. J.E.Luce

It is the downward part that I mean.

Dr. J.R.Parker

Yes I do take your point. May I say, on reflection, that your suggestion is reminiscent of Taylor's work (15) on the instability of free surfaces and, in particular, its experimental verification by Lewis (25). Lewis clearly demonstrated how the upper surface of a layer of liquid was disrupted when accelerated downwards by compressed air. However, there was no indication from his experiments that any of the liquid rose above the initial level of the liquid surface. On the contrary, the photographs he published show that every part of the liquid acquired a downward velocity. Even though sharp upward pointing tongues of liquid developed at the upper air-liquid interface, their tips moved downward at perhaps half the velocity of the bulk of the liquid. Thus Taylor instability cannot explain how spray droplets are thrown upwards from the wire; to account for this the upward acceleration of the wire after each drainage element must also be considered.