Calender barring review with experiences

JAKE ZWART

ABSTRACT: Excessive calender vibration affects all styles of calender stacks from single to multi-nip, all hard rolls, or a combination of hard and soft rolls. Calender vibration can be forced vibration or self-excited vibration. Forced vibration occurs at the first few harmonics of the calender roll rotational speeds and is caused by imbalance, misalignment, eccentricity, etc. Self-excited vibration, the focus of this paper, occurs at higher frequencies.

Feedback paths for self-excited vibration must be understood in order to ameliorate the problem. This is presented in the context of the historical development of the theory of self-excited feedback mechanisms, followed by a survey of self-excited feedback mechanisms in various types of calender stacks. Methodology to determine which feedback path is present and techniques to control or eliminate the resulting vibration follow. To obtain a flavor of the types of problems faced and practical remedial actions, a variety of experiences with barring issues are provided.

Application: This paper provides background information on the history of calender barring on a calender stack, along with the factors that contribute to the problem and resolutions to the problem.

Calender barring is vibration of calender rolls resulting in caliper variations with accompanying gloss and opacity variations. This paper focuses on calender vibration due to self-excited vibration and not the forced vibration due to typical rotating equipment phenomena such as imbalance, misalignment, eccentricity, etc. Self-excited vibration starts when random disturbances excite a resonance in the calender, resulting in caliper variations in the paper and/or barring marks on the roll, which act as an excitation source after a time delay.

A simple contrived example that is useful for understanding the self-excited concept is the playground swing. When the force of a push on the swing is in phase with the velocity of the swing, the amplitude of the swing increases. When the force is applied out of phase with the velocity, the amplitude quickly decreases. Here, the person pushing on the swing mimics the time-delay feedback mechanism.

Self-excited vibration is not unique to calender stacks. The machine tool industry is plagued with this problem, with early research funded and performed by Cincinnati Milacron [1] in the 1950s, going right up to modeling a 5-axis milling machine [2] in modern times. The steel industry faces similar problems where the word chatter is used instead of barring in rolling mills. Press section vibration can also be the result of self-excited vibration. Time delay differential equations [3] are the fundamental equations used to model all self-excited vibrations.

Calender barring in multi-nip hard roll stacks has been recognized in papermaking literature for a long time, with the first reference being a private communication between Bercel [4] and an E.B. Eddy employee in 1950, with the first written papers [5-7] dating back to the early 1960s. In 1966, the MASc thesis of Davidson [8] shows the feedback paths we know today were still under debate. In the early days Bowater Technical Services contributed greatly to the understanding of calender barring. By 1975, Parker [9] gave a good summary, indicating calender barring was well understood, which was echoed by Cotgrove [10] a decade later. Their summary is included in the next section under caliper feedback and corrugated surface feedback for multi-nip hard calenders.

CALENDER BARRING VIBRATION FEEDBACK MECHANISMS

The feedback mechanism for self-excited vibration is a variation induced by the process, which then acts on the same process as an excitation after a time delay. A forced vibration, on the other hand, is intrinsic in the system and acts without a time delay.

Multi-nip hard roll calender with caliper feedback

We can think of each calender roll in a multi-nip stack as a rigid mass with vertical translational motion, with the paper in the nip acting as both a spring and a damper. This system yields one natural frequency per roll. The lowest natural frequency occurs when all of the rolls move in phase with no relative movement between the rolls, resulting in no caliper variations. For the remainder of the natural frequencies, assuming the damping is viscous, the rolls will be in phase or out of phase with neighboring rolls. The out of phase motion between adjacent rolls results in caliper variations.

An impulsive disturbance excites all frequencies, with the response proportional to the amplitude of its natural frequencies. Thus, the response is sinusoidal vibrations at the resonant frequencies of the stack, resulting in sinusoidal caliper variations. Any caliper variation induced by an upper nip will travel to the lower nips, acting as an excitation after a time delay. If the caliper is increasing as the rolls in the lower nips are moving apart, the vibration is sustained or increases. Stated quantitatively, this occurs when there are an integer-plus-one-quarter (N+1/4) wavelengths between an upper and lower nip. Conversely, if the rolls are moving towards each other when the caliper is increasing, the force acts to reduce the vibration level. The number of wavelengths between nips is controlled by the calender offsets. The offset is defined as the machine direction centerline distance of the rolls relative to the fixed roll, usually the king roll. Most calenders can extend or retract the pivot arms. On older A-frame calender stacks, shims are used to offset the rolls.

This type of self-excited multi-nip hard roll calender barring can start or stop instantaneously with a change in machine operating conditions. Important operating conditions are the machine speed and the parameters that change the stiffness of the paper in the nip. Fortunately for many machines, these parameters are relatively constant.

The investigation of the actual behavior of paper in a nip has been modeled by Browne [11]. Shelley [12] inverted this model to determine the nonlinear stiffness properties of the paper in the nip, and then used the stiffness to solve for barring in the time domain using time delay differential equations [3]. His four-roll stack model indicated changing calender speed could induce or prevent barring.

Bercel [4] created a model of the vertical vibration of a calender stack in which the vibration along the length of the roll was considered. Melnick [13] used finite element methods to extend the standard calender offset calculation procedure by creating a two-dimensional model of the dynamics of a calender stack. This is used to generate a set of roll offsets to counter the tendency to vibrate.

Corrugated surface on hard calender roll feedback

All paper furnishes have some level of abrasiveness. Fillers such as precipitated calcium carbonate (PCC) and ground calcium carbonate (GCC) greatly add to the abrasiveness, increasing calender roll wear. The wear rate is proportional to the nip load.

If the resonant frequency is at an integer multiple of the roll rotational speed, the wear will occur at the same circumferential location and will eventually wear a corrugation pattern into the calender roll. The wear rate will increase exponentially until it is limited by system nonlinearities. Consistent with other research in self-excited vibration, Parker [8] found that the bar marks on the roll rotate slowly around the circumference of the roll.

Single-nip soft calender thermal barring

Chinn [14] discusses the effect of thermal barring on a soft roll in a press section where vibration causes a circumferential temperature variation, which in turn results in modulus variations around the circumference of the roll. The modulus variation in the cover then acts as the exciter in the nip. Chinn also discusses the anomalous vibration characteristics of polymers that act as nonlinear springs in the nip.

Single-nip soft calender creep barring

Polymers exhibit creep, a time dependent behavior governed by the relaxation time constant [15]. The increased deformation at the circumferential location where the rolls are closest together in the vibration cycle takes time to fully recover due to the time-dependent behavior. Before this recovery is complete, the partially deformed roll enters the nip again, with the remaining nonuniform deformation acting as the excitation force. It is probable that the relaxation time constant and thermal barring act in tandem.

Peripherally drilled rolls

Peripherally drilled rolls, when heated, induce a nonuniform thermal expansion to form a polygon shape, with a difference in roll radii of 2–3 μm [16] when the roll surface temperature reaches 200°C. In most calenders, the effect will be more modest, as they have lower surface temperatures. This is an exciter for forced vibration, and to the author's knowledge has never been associated with barring problems.

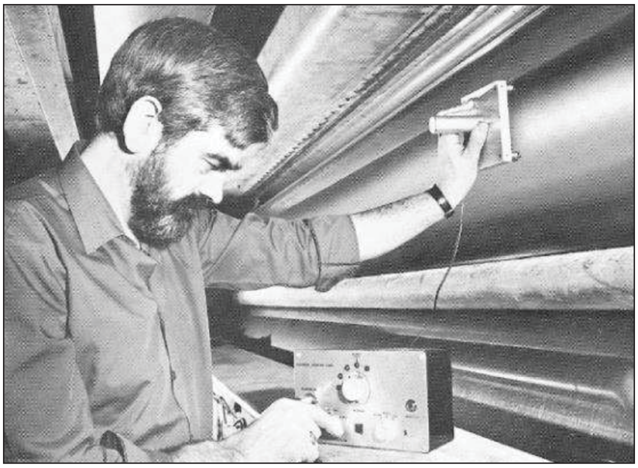
STEPS TO RESOLVE BARRING ISSUES

Measurement of barring

Barring is typically detected by high vibration, noise, and sheet quality variations. Quantifying the vibration has mainly been determined by one of two methods. The first is measuring the paper properties. This is best achieved by taking a butt roll of paper and measuring the caliper and gloss variations with an offline profiler such as the Tapio Paper Machine Analyzer [17]. The caliper gauge of an online scanner can also be used in single point if the frequency response is sufficient for the frequencies present. Since caliper reduction and gloss formation occur in tandem, many early papers mention a gloss sensor to measure barring on the machine [10], as it has extremely good frequency response.

Severity	Vibration Velocity, mm/s rms
Very severe	10
Severe	5
Moderate	2
Acceptable	1
Good	0.5

I. Calender roll vibration severity.



1. Bowater Technical Services (BTS) electronic curvature gauge.

Effect/Roll Condition	Size of Corrugation, peak to peak
Very severe barring	Over 20 µm (0.0008 in.)
Severe barring	Over 10 µm (0.0004 in.)
Moderate barring	Over 5 µm (0.0002 in.)
Seen in paper	2.5 µm (0.0001 in.)
Reground roll target	Less than 1.0 µm (0.00004 in.)
New roll condition	Less than 0.5 µm (0.00002 in.)

II. Hard roll corrugation severity.

The second commonly used method is to measure the vertical vibration of the calender roll bearing housings. **Table I** shows a table for the vibration severity on the calender roll bearings. One of the shortfalls of measuring the vibration on the bearing housings is the assumption that the bearing housing vibration is identical to the roll vibration. Ideally, the roll vibration should be measured directly. Kiviluoma [18] discusses a number of methods for measuring the roll vibration, citing their advantages and failings. He then develops a method to overcome the shortcomings, using an accelerometer mounted on a sliding base.

More recently, video operating deflection shape analysis [19] and motion amplification [20] show promise to resolve this problem as well. With these techniques, one must ensure sufficient resolution to measure micrometer level displacements at the frequencies of interest.

Corrugations on a calender roll were first measured by Parker [21] using a dial indicator mounted on a platform with feet held against the roll. Bowater Technical Services (BTS) refined this technique by replacing the dial indicator with a displacement sensor and a primitive display called the electronic curvature gauge as shown in **Fig. 1**.

Corrugation severity on a roll

BTS [22] gives a range of amplitudes of corrugations in a roll with the corresponding severity, as shown in **Table II**. FPInnovations has more recently confirmed these results in several documented case studies [23].

Distinguishing between barring sources

The best approach to resolving a calender barring issue is to ensure the problem is understood. Understanding the different characteristics of the vibration between the feedback due to the paper caliper variations and a corrugated roll is crucial. **Table III** gives a number of indicators to determine the type of feedback for a multi-nip stack. For a single-nip stack, there is no feedback path through caliper variation.

Step-by-step diagnostic procedure

With this background, the following procedure will aid in determining which feedback path is causing the barring problem:

1. Review what is known about the barring phenomena.
   a. Does it come and go with grade and/or speed changes?
   b. Has it been increasing slowly over time?
   c. Have paper samples been tested on a Tapio or other offline profiler to obtain the magnitude and frequency of barring?

Symptom	Caliper	Barred Roll
Barring frequency at an integer multiple of a roll rotational frequency		Yes
Barring has roll running speed sidebands		Yes
Vibration increases steadily (or exponentially) over the course of days, weeks, or months		Yes
Barring will stop or start instantaneously	Yes	
Barring frequency is not an integer multiple of a roll rotational frequency	Yes	
Measured barring on a calender roll with a barring gauge is greater than 1 µm p-p		Yes

III. Feedback source for multi-nip stack.

   d. Have single point caliper or gloss measurements been taken from the online scanner? Take care with the frequency response of online gauges.
2. Take vibration measurements and analyze using Table I and Table III.
   a. *Ideal measuring procedure* — Take vibration measurements on each bearing housing simultaneously with tachometer readings from each roll using a multi-channel vibration data acquisition system along with the paper caliper and/or paper gloss readings.
   b. *Normal measurement procedure* — Take vertical vibration measurements at barring frequencies, using a predictive maintenance vibration data collector to obtain spectra from each calender roll bearing along with the rotational speed of the calender rolls.
   c. Perform these measurements on a scheduled basis.
3. If the problem is paper caliper feedback:
   a. Generate optimum offsets for the grade manufactured most often, at normal operating speed. This requires information about the calender stack and the vibration spectra from the calender roll bearings.
4. If the problem is indicative of calender roll corrugations:
   a. Utilize a barring gauge to determine the barring level on the calender rolls in the existing stack and ensure there is no residual barring on rolls being changed into the stack.
5. Single-nip stack — Vibration is at a harmonic of roll rotational speed (caliper feedback is not present).
   a. Permanently corrugated roll:
      • Vibration is present immediately upon startup.
   b. Creep or thermal feedback:
      • No vibration at startup, but increases during operation, possibly taking an hour to build up.
      • Take infrared temperature measurement of cover.

Caliper feedback

A calender roll is offset when its machine direction position is not directly above the king roll. This changes the paper wrap length from the nip above the roll to the nip below the roll, which in turn affects the number of wavelengths of caliper variation from one nip to the next.

To determine the offsets, first a dynamic model of the calender stack is required. An N-roll calender stack is modeled as an N-degrees of freedom (DOF) system with the paper in the nip acting as both the spring and damping. The model requires the mass, damping, and spring constants of the system. The roll masses are obtained from the engineering drawings or by weighing the rolls. The spring constants are determined from the natural frequencies. Since the vertical vibration is the motion that imparts the caliper variation and barring occurs at the natural frequencies of the calender stack, the natural frequencies are determined from the barring frequencies using the vertical vibration on the calender roll bearing housings, or the gloss or caliper spectra, while the machine is in normal operation. The damping value is assumed.

Any parameter affecting the amount of paper and its density in the nip affects the paper spring constant and thus changes the dynamic model. According to the calendering equation developed by Crotogino [24], the parameters that control the paper bulk (inverse of density) exiting from the nip are the ingoing bulk, furnish, nip load, machine speed, harmonic mean of the roll radii, mid-nip web temperature, and web moisture content. Of these, and assuming a reasonably constant furnish, the most sensitive parameters will be the ingoing bulk (caliper/basis weight) and the nip load. Speed also affects the caliper, but even more importantly, it affects the travel time of the paper from one nip to the next.

Caliper variations induced in an upper nip can act as an exciter in all of the subsequent nips. However, intermediate nips will diminish the magnitude of the caliper variation, and this needs to be accounted for in the model. Each natural frequency that is contributing to the barring problem is included in the model. In practice, the lowest barring frequency for a multi-nip hard calender is normally in the 80–90 Hz vicinity.

Once a dynamic model of the calender stack has been created, it is used to determine the optimum set of offsets. As the roll offsets are changed, the nip-to-nip wrap length also varies. The offsets giving a wrap length of N+3/4 (N is an integer) wavelengths of caliper variations between one nip and the next are ideal. Mathematically, this is determined by finding the global minimum of the regenerative tendency, where the regenerative tendency is the positive work (dot product of force and displacement) done in a nip for all the natural frequencies.

Because conditions change over time, and since the diameter of each calender roll is unique, offset calculations are recommended for every stack change for problem machines.

Corrugated roll

If the feedback path has been determined to be a barring pattern on the rolls, then the rolls must be removed and reground to remove this pattern. The barring amplitude should be measured both before and after the roll grind to ensure that there is no invisible residual barring in the roll. If the roll life is short, then the abrasiveness of the furnish needs to be checked.

The barring pattern on a roll slowly rotates around the roll in one direction if the barring is getting more severe, and in the opposite direction if the barring is reducing in severity. This can be used as an early warning indicator of a change in barring severity with an appropriate online monitoring system installed.

Damping

Another potential resolution for calender barring regardless of the feedback path is to add damping to the system. An industrial damper [25] is available that is used extensively on single-nip soft calenders with low nip load on tissue machines. The Vibrosoft swimming roll [26] has built-in damping designed into the swimming roll portion. Its damping frequency range is 20–80 Hz but is most effective at 40–60 Hz. This limits its usefulness for typical barring problems where the problem frequencies tend to be 80 Hz and higher. Bearing systems with integral damping [27,28] are another means to add damping in principle. These dampers are only likely to work on the king roll and not with the calender rolls on pivoting arms.

CASE STUDIES

This section provides some brief vignettes of barring experienced by different mills. Most are for multi-nip hard calenders, some are for different types of calenders, and a few are from other areas of the paper machine, as they are enlightening.

Offsetting calender rolls

A paper machine with a 5-roll calender stack was experiencing calender barring. The mill decided to trial offsets provided from multiple vendors and found the offsets from different vendors varied and the performance of the offsets were not all equal. This variation is likely due to the large number of factors that must be accounted for in modeling calender barring. Implementing offsets from the preferred vendor has controlled the vibration from the calender stack, with the vibration normally staying within 1 mm/s at barring frequencies.

Newsprint calender stack

A newsprint calender stack was having barring problems to such an extent that nearby offices were uncomfortable due to barring noise. The tone (frequency) of the sound changed with operating conditions. A vibration survey was performed in which the vibration and rotational speed of all the calender rolls were simultaneously measured.

The barring on the rolls was measured with a barring gauge developed by Spectrum Technologies (Puslinch, ON, Canada). While some variations were found, there was not an integer number of corrugations in a revolution, nor did the roll corrugation wavelength coincide with the barring wavelength, confirming that the rolls were not the feedback path for the self-excited vibration.

On the first day of measurements, the 45 g/m^2 paper showed the dominant vibration was at 127 Hz, with an amplitude of 2.5 mm/s on the bearing housings. Listening to the sound while walking along the calender catwalk, the noise was much louder at the center of the machine than at the drive or tending sides.

The measurements were repeated the next day on 48.8 g/m^2 paper. This time the main frequency present was 218 Hz with a peak amplitude of 10–15 mm/s on the bearing housings. The sound was much higher at the ends than at the center of the machine.

When operating deflection shapes were taken near the pivot pin assembly, differential movement was detected. This led to the suspicion of excessive looseness at that location, and recommendations were made to resolve the problem.

Offsets were generated for this machine that alleviated the barring problem.

After a number of years, the vibration level on the calender stack started to increase. Measurements taken by the predictive maintenance crews showed the vibration increasing with time over the course of a month. This indicated the rolls were becoming corrugated and needed regrinding.

Online supercalender barring

A mill was having barring problems on an online supercalender. When they learned about offsetting calender rolls in conventional hard-nip calender stacks, they moved the fly rolls to see if changing the nip-to-nip paper length would help. This change resulted in improved runnability [29].

Impact of breaker stack use

A newsprint mill was normally operating with very little barring with a 6-roll calender stack while the breaker stack was in operation. As soon as the breaker stack was lifted, the calender started barring, with calender vibration levels increasing by about two orders of magnitude. When the top calender roll was subsequently lifted, the barring immediately stopped.

This type of barring is regenerative feedback through paper caliper variations, showing paper properties are important in determining barring propensity.

Paper abrasives

A groundwood sulfite mill had a history of barring. At different times, the bar marks could be seen across the face of the roll, at the center only, at the roll ends only, and even at one end but not the other. The bars were usually spaced at 3/8 in. to 3/4 in. apart.

Items that improved stack life were:

- Moving the intermediate swimming roll to the top position and changing the load relief settings, combined with operators adjusting edge relief to control barring.
- Improved calender roll grinding.
- Installation of cleaners to remove groundwood grit.
- Replacement of the entire stack rather than just the barred roll.
- Implementing offsets predicted from a mathematical model; this produced limited results, likely because the feedback path was through calender roll wear rather than paper caliper.

2. Damage to roll cover, including chunks of cover removed due to barring.

- Using an electronic curvature gauge on every shutdown to monitor the condition of the rolls; freshly ground rolls were also checked to ensure no residual barring was present.
- Monitoring the vibration on the roll bearing housings.

At the beginning of this process, stack life was often as little as 3–4 weeks. Once complete, stack life was 4–7 months.

Single nip with covered roll

In a single nip of a covered pressure roll without crown compensation against a dryer can, a trial was performed to find the optimum nip loading. When the nip load went to roughly double the design nip load, the vibration increased drastically at 6x roll rotational speed, resulting in damage to the rubber cover, with some locations having pieces of rubber removed from the cover, as shown in **Fig. 2**. The damaged locations were uniformly spaced around the circumference.

The rubber cover could handle a uniform CD nip load without a problem, but as the nip load increased, the loading became nonuniform, with increased loading near the edge. Once the nip load at the edge reached a critical value, the cover could not recover its original material properties before reentering the nip, resulting in hot spots at the edge of the roll, as measured with an infrared camera. These hot soft spots acted as an exciter the next time they entered the nip, increasing the temperature to the point of failure.

Soft nip calender barring

A soft nip calender stack with low nip loads was prone to barring. The barring frequencies occurred at 5, 6, and 7 times the covered roll rotational frequency, depending upon machine speed and operating conditions. Both vibration and cover temperature were monitored.

When the nip load was increased, the vibration increased first, followed by a cover temperature increase and thermal barring on the cover. The vibration and temperature frequencies were identical, confirming a thermal barring problem — or a combined creep and thermal barring problem.

Additional damping at each end of the roll was used to eliminate the barring.

Dryer gear mesh frequency

Vibration measurements around a calender stack prone to barring found the dryer gear mesh frequency coincided with a barring frequency. The mill removed the closest idler gear and found no improvement.

One of the calender natural frequencies coincided with the dryer gear mesh frequency, and the dryer gear mesh frequency was part of the ambient vibration exciting the resonance. The remaining ambient vibration with the idler gear removed was sufficient to excite the vibration.

After the installation of a new multistage screen to remove grit, and the use of calculated offsets, the barring was greatly reduced.

CONCLUSIONS

This paper reviews the history of calender barring literature, putting barring into a solid theoretical context. When properly understood, self-excited vibration is not as daunting as when it is first encountered. Specific symptoms can be used to determine which feedback path is present.

If the problem is feedback through caliper variations, offsetting the rolls is an effective way to manage the vibration. New offsets are calculated for each stack change.

Dampers are extensively used on lightly loaded soft calenders used in the tissue industry.

If the problem is feedback through calender roll corrugations, a barring gauge is an excellent method to measure the corrugations on the roll and provide guidance on when the stack should be changed. An online monitoring system is suggested to determine if the corrugation pattern is becoming worse over time.

With these strategies, barring issues are successfully managed. **TJ**

ABOUT THIS PAPER

Cite this article as:
Zwart, J., *TAPPI J.* 21(7): 377(2022).
https://doi.org/10.32964/TJ21.7.377

DOI: https://doi.org/10.32964/TJ21.7.377

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

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ABOUT THE AUTHOR

I chose to study this topic because it is an ongoing area of concern in paper mills, and a broad overview paper giving insight is important for younger engineers. This paper is a survey of the existing research into calender barring, stressing the reasons for barring and what can be done to eliminate or minimize its effect. It concentrates on giving the mill engineer an intuitive understanding and ways to diagnose the problem.

The most difficult aspect of this study was validating some of the modeling assumptions by taking mill measurements of the vibration. Personally, I discovered that research into calender barring has mostly been accomplished within my lifetime. Also interesting was that the calender barring model to predict offsets works surprisingly well, despite some of the assumptions seemingly being violated.

Mills that experience calender barring (and press barring, though that is not the focus of this paper) can use the results of this paper to understand what is happening and where they can go for help. The next step in this research is to measure the difference between the bearing housing vibration and the roll vibration. Another next step is a proper modal test, or at a minimum an operating modal test, on a calender stack.

Zwart

Zwart is principal at Spectrum Technologies in Puslinch, ON, Canada. Email Zwart at jake.zwart@spectrum-tec.com.

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