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Methods and Tools Used in Paper Machine Supercalender Vibration Diagnostics

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ABSTRACT

Supercalender sections in the paper manufacturing process are arguably among the most prone to severe vibration problems. Supercalenders are machine sections with their own paper reel unwind and rewind stands and are used to impart a very high quality surface finish to paper to enhance its printability. Denim and polymer covered rolls used in supercalender operation are designed to deform in the nip, leading to very difficult to troubleshoot vibration problems. The noise generated in and around the machines when the worst vibration phenomena occur can be intolerable for operating personnel and while the industry has adopted a variety of condition monitoring strategies, they have typically failed in the complete diagnosis of supercalender vibration issues. This paper discusses the use of a high performance, multichannel dynamic signal analyzer and methods used towards the complete characterization of supercalender vibration problems at a paper mill, leading to successful reduction in noise levels and significantly increasing component life and enhancing product quality.

INTRODUCTION

Permanent condition monitoring is employed to varying extents on most paper machinery. Although entire machines may be instrumented for online monitoring of vibration, pressure, temperature and other process signals, it is usually the most critical equipment that is set up for automated data acquisition and diagnostics. Single channel data collectors, used by technicians to perform route based measurements across machinery and/or an entire plant, still makes up the majority of the condition monitoring effort. The data is then uploaded to a system database that provides trending and some automated diagnostics tasks [1]. Permanent monitoring systems typically use multiplexed acquisition of signals, with very few, if any, signals acquired simultaneously. These systems incorporate a single analog-to-digital converter with a high-speed selector switch accessing signals from multiple sources [2]. So, while there may be a large number of signals being acquired, cross channel measurements such as relative amplitude and phase are not possible.

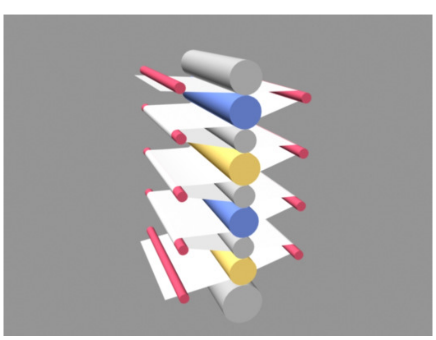

Figure 1. Schematic of Supercalender Section

MACHINE AND PROBLEM DESCRIPTION

Supercalender sections in paper producing plants are standalone machines that pass paper through a stack of rolls and are designed to control the caliper and surface finish of the paper. Obviously, the roundness and mechanical condition of the rolls needs to be maintained at the highest possible levels as they can generate both localized and system-wide vibration and identifying the 'bad' rolls can often be an impossible task with the aforementioned instrumentation. 'Filled' rolls, shown in blue in Figure 1 and polymer covered rolls, shown in yellow, are the rolls used to impart a highly polished finish to the paper.

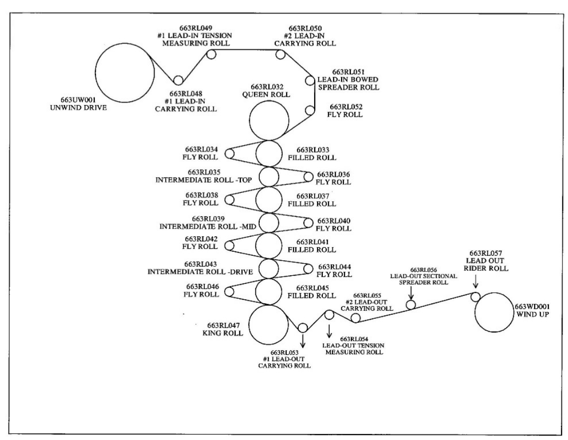

Figure 2. Front Elevation of Supercalender Section showing Unwind and Rewind Stations

Figure 2 shows the front elevation of the machine section showing the paper reel unwind and rewind stands. It should be noted that every roll seen in this figure can and often does contribute to the overall machine vibration and determining which rolls contribute the most and why is an eternal challenge for the test engineer. The following are important considerations for the test engineer attempting to characterize supercalender vibration:

- Supercalender sections are often hot, dirty environments
- Access to measurement locations is difficult
- Multiple rolls all contribute to the onset of problems
- The need for tachometer signals from all rolls for 1/rev phase trigger reference
- Machine speed rarely remains constant
- Vibration severity charts do not adequately address supercalender vibration
- Softer rolls are designed to deform under nip pressure and are inherently vibration sources
- Stack dynamics are extremely complex
- The need for several simultaneous vibration and tachometer measurements to attempt diagnostics

Figure 3. Supercalender Section Being Studied

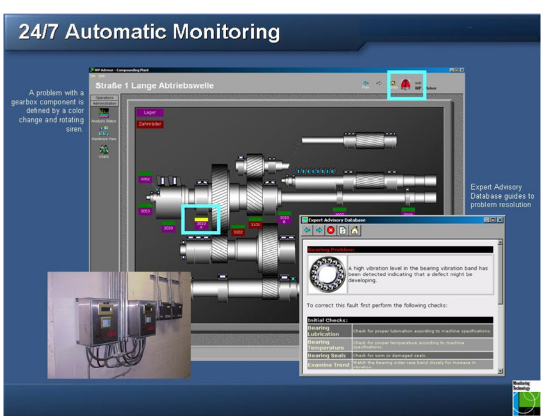

Figure 4. 24/7 Condition Monitoring System Screen (Picture Courtesy of Monitoring Technology Corporation, Fairfax, VA)

Figure 5. Multiple DSPCentric Abacus Chassis Networked for Larger Channel Count Field Data Acquisition and Analysis

The key to successful and sustainable diagnostic efforts on paper machinery or in the maintenance/manufacturing shop is in using the right instrumentation and applying fundamentally sound testing practices. While condition monitoring tools do provide an early warning of impending problems if applied correctly, they are rarely able to help identify the nature and source of many serious problems. The use of a dynamic signal analyzer with a highly flexible and extensive range of measurement solutions is necessary. Because these instruments are designed with ease of portability and scalability in mind, any type and number of sensors may be easily employed in the diagnostic efforts in practically any test environment.

For the machine shown in Figure 3, multiple triaxial sensors are needed on both sides of the machine (tending and drive sides) and tachometers need to be placed at each roll. Permanent condition monitoring systems like that shown in Figure 4 typically never have such instrumentation capability. A multichannel, expandable analyser like the Data Physics SignalCalc Savant analyser powered by the Abacus hardware platform seen in Figure 5 allows 32 input channels and 8 tachometer channels per chassis.

THE SOLUTION

Many predictive maintenance and reliability personnel are now turning to high performance dynamic signal analyzers that offer highly mobile test platforms with significantly increased capability, both in input channels and analysis software. A recent advance in technology, gaining popularity in the industry, is the Abacus hardware platform. Its unique DSPcentric design involves high performance signal processing, including digital decimation at the hardware level that in turn frees up the host computer for display and measurement storage [3]. The chassis may contain from 1 to 4 modules, each module consisting of 8 input channels, 2 output channels and 2 tachometer channels. Each module contains a Gigaflop Digital Signal Processor to provide the computational power. The input and output channels use 24 bit ADCs and DACs. The chassis uses a Pentium processor to supervise traffic and supports streaming data to a 350 Gigabyte local disk at an aggregate rate of 20Mbytes/sec.

Dynamic Signal Analyzer Architecture

Abacus is a significant architectural advance. Each module contains its own signal processor as shown in Figure 6. The DSPcentric design is essential to the high realtime analysis bandwidth of the system. Even after decimation filtering the

1 Gigaflop DSP has plenty of spare capacity to always maintain realtime measurements. Whether operating at its maximum bandwidth of 49 kHz or a low 1 kHz, tri-spectrum average measurements with selectable overlap are available in realtime.

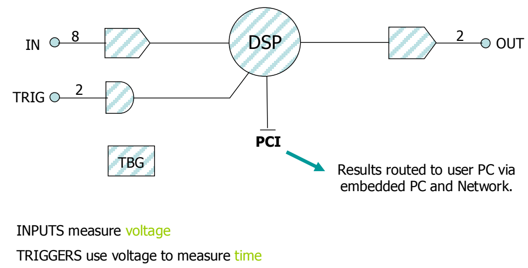

Figure 6. Architecture of Single Abacus Board

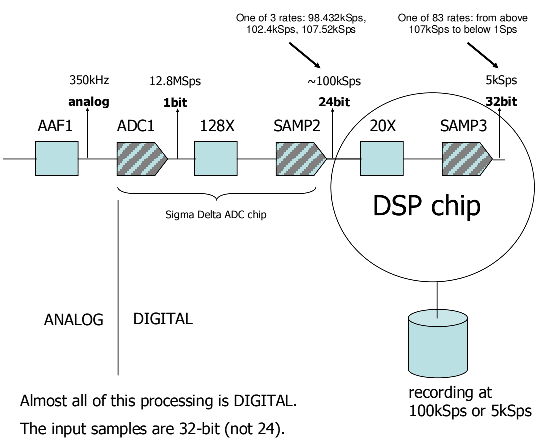

Figure 7. Flow of Data Through ADCs

Each chassis contains its own disk storage. The local bus disk is essential to the high realtime recording rate of the system. The system uses the 132 MHz PCI bus within each chassis for optimum performance and availability of off-the-shelf components. Ethernet connectivity enables host PC-to-front end as well as wide area network communication.

Specifications for Dynamic Range, Signal to Noise ratio, Total Harmonic Distortion, Alias Rejection and Channel-to-Channel match show that Abacus is an analog front end that does justice to the 24 bit digitizers. It is the first time that a dynamic signal analyzer is able to deliver a 150 dB dynamic range in a spectrum, the entire potential of the 24-bit ADC. Figure 7 shows the flow of data through the ADC. At its full bandwidth, the input dynamic range is 120 dB, a testament to the analog design and the 24-bit Delta-Sigma technology. Robichaud [4] has prescribed a dynamic range of at least 114 dB for machinery diagnostics applications, but with the technology readily available, that specification is almost obsolete. Many test and measurement experts believe that the sensor can be allowed to be weakest link in a measurement chain. That is not true of the analyzer used for any type of vibration testing.

At lower bandwidths the dynamic range increases, reaching 150 dB at bandwidths below 1000 Hz. The answer lies in signal processing; onboard DSP is used for decimation filtering with selective noise rejection. The front end analog anti-alias filter (AAF) has a cut-off frequency of 350 kHz. Following anti-alias filtering the data passes through various stages of the Delta-Sigma ADC (stage 1 being a 12.8 MSps modulator or high frequency converter), where the data has 1 bit resolution. After that the data is digitally downsampled 128 times to yield one of three primary sample rates, all around 100 kSps (42 kHz), and the data is now 24 bit. Finally, the data is processed in the DSPs, where further downsampling occurs as needed. For the example in Figure 7 the final data is 5 kSps, and is 32-bit floating point precision. It should also be noted that the incoming data stream can be recorded to the local bus disk at the analysis bandwidth or at a different bandwidth, derived from the same initial clock rate.

ANALYSIS METHODS

General Test Methodology

Problems on paper machinery stem from a variety of sources. The following are factors that affect machine performance and sensitivity to vibration issues:

- Roll diameter
- Shell thickness
- Roll cover material and stiffness
- Number of rolls in stack
- Roll offsets
- Machine width
- Machine structure mass, stiffness and damping
- Roll manufacturing and/or reconditioning
- Unwind and rewind stand dynamics
- Operating speeds
- Condition of bearings, drive shafts, couplings, etc.
- Electrical drive tuning
- Paper chemistry, caliper, density, surface quality
- Machine Foundation

Unlike with condition monitoring practices, proper diagnostic efforts require the use of various data acquisition and analysis techniques, during both machine operation and shutdown conditions. In general, the following phases should be applied to a given problem:

Normal Operation Survey

During this phase, data is acquired with the machine in normal production mode, on rolls and supporting structural framework. Assuming that the focus of the analysis is on rolls in a given machine section, it is essential that data be acquired on every roll, on each bearing housing, in three orthogonal directions as shown in Figure 8. If certain rolls are nipped up to other rolls, then the measurement directions should be adjusted so that the radial vertical transducer now points in the direction of the nip, with other orthogonal axis being the direction perpendicular to nip. Collecting data in three directions at each measurement location allows for the future construction of operating deflection shape (ODS) models.

One powerful tool used in the troubleshooting of roll related vibration is synchronous averaging which requires a 1/rev tachometer signal for each roll in the system.

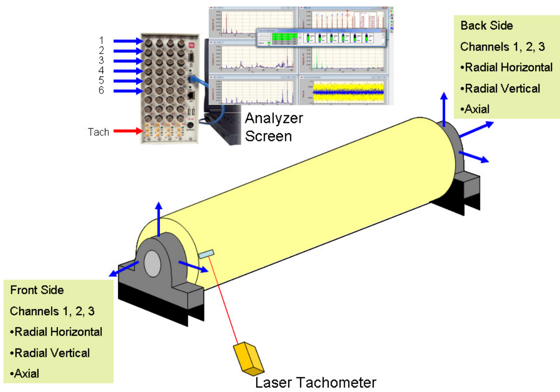

Figure 8. Recommended Minimum Number of Sensors for Roll Analysis

During this phase of measurement and analysis, common problems such as roll unbalance, misalignment, looseness, roll cover corrugation and bearing defects may be identified easily. However, care should be taken to ensure that sensors be placed as close to the bearing load zones as possible.

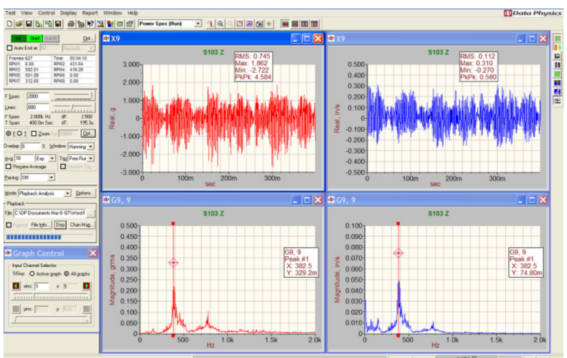

Figure 9. Simultaneous Time and Frequency Domain Analysis using Multiple Engineering Units

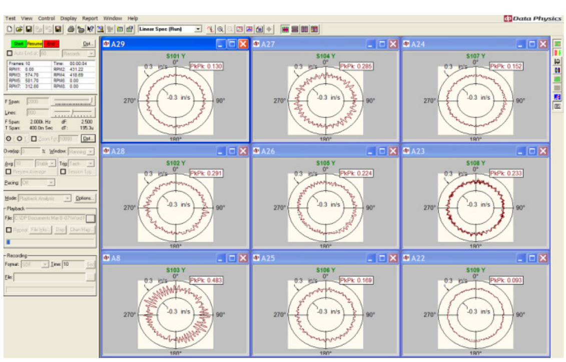

Figure 10. Easy Identification of Problem Locations (note: Dynamic Roll Profiles Show Possible Roll Surface Corrugations)

Figure 9 shows time and frequency domain measurements being simultaneously made in both units of velocity and acceleration. This allows identification of dominant vibration sources (from frequency content), the overall nature and severity of the vibration (from time signatures). Acceleration is proportional to the amount of force exciting the system for a given amount of dynamic mass and velocity is proportional to the amount of energy being dissipated through vibration and therefore the damage potential. Displacement is also useful as it can be used to determine the amount of relative motion between adjacent surfaces. Figure 10 shows synchronous time average data presented in polar format, useful in determining the roundness of rolls in the supercalender stack and the way vibration changes as a function of roll rotation.

Speed Trials

In order to identify natural frequencies in the system, the machine is typically accelerated and then decelerated through its operating speed range. This, however, results in an interruption to normal production and generally, only time enough for one or two ramps (called speed trials) is available. Therefore, it is imperative that as many locations as possible be instrumented with sensors for a given test run.

During speed trials, the paper web is taken off the machine and either the entire machine or individual sections are accelerated up to and decelerated down from some maximum speed with a controlled ramp rate. The maximum speed may be either the drive limit or a speed deemed safe by the machine operators. This phase of analysis allows for easy determination of natural frequencies that would be excited within the operating speed range of a machine. Figure 11, a waterfall plot showing vibration amplitude as a function of frequency and machine speed, shows the ramp up of the supercalender section with vibration measured on a roll in the radial horizontal direction. Using order analysis techniques, the analyst can easily track multiples of roll rotational frequency as they pass through various speeds, clearly pinpointing the presence of resonance frequencies and allowing easy determination of the range of speeds to be avoided until a structural modification is made, by analysis of the width of the resonance band.

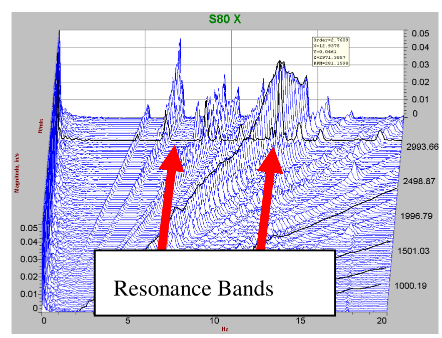

Figure 11. Identification of Low Frequency Structural Resonance Bands

Figure 12 shows another waterfall plot over a wider frequency range, using color to signify the vibration severity.

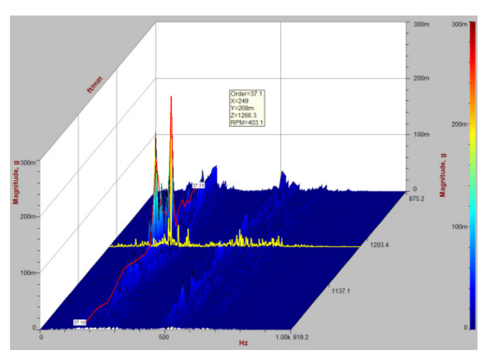

Figure 12. Identification of Higher Frequency Stack Resonance

Operating Deflection Shape (ODS) and Mode Shape Analysis

An operating deflection shape analysis (ODS) consists of acquiring vibration data (under normal operating conditions) in three directions at various points on a machine (framework, rolls, etc.). This is done by maintaining an accelerometer at a fixed, reference location on the structure and then roving triaxial accelerometers around the structure. Obviously, having a large number of input channels in the data acquisition system greatly shortens the time required to acquire all the data. The machine speed should be maintained as constant as possible during the data acquisition phase. This is typically not a problem for paper machinery, although some preparation and planning is essential, but on supercalenders it is much more difficult as the normal production speeds rarely remain constant. The fixed accelerometer measurement provides the reference for phase measurement between all measurement locations.

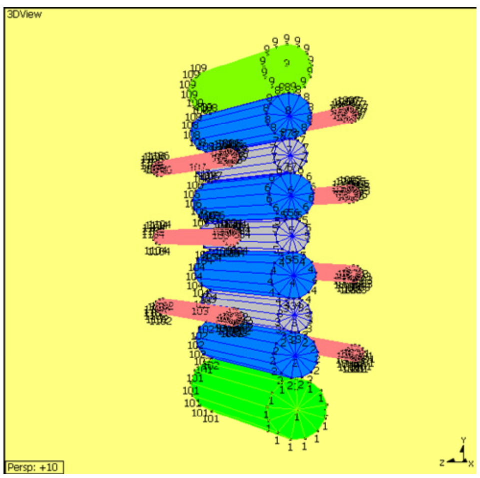

Figure 13. ODS Model of Supercalender Section

The data is then processed using modal analysis software to allow animation of a three-dimensional model of the structure, showing relative amplitude and phase between all measured points, at any selected frequency. Figure 13 shows the model constructed to approximate the supercalender roll stack. Triaxial vibration measurements were made at all roll bearing locations, including the fly rolls that are used to turn the paper travel direction back through the stack.

The differences between operating deflection shapes and mode shapes are explained in detail by Richardson [5]. There are two types of natural frequencies that affect roll systems. In the first case, natural frequencies of the rolls themselves may be excited at what are called critical speeds. In the second case, rotational frequencies of rolls excite natural frequencies of the supporting structure or in some cases, an entire machine section. If the normal operating condition data is fit to natural frequencies of the system, identified in the speed trials, the resulting shapes obtained in the modal analysis software are experimental mode shapes.

Frequency response function measurements, derived from cross spectral measurements between multiple input channels and one or more reference channels are also simultaneously exported to external modal analysis software formats (e.g., MeScope) so that operating modal and ODS analysis may be performed to provide clear visualization of the motion of different points in the system.

Figure 14 shows the first machine direction natural frequency of the entire supercalender roll system and structure at 7.2 Hz, characterized by a front to back rocking motion and that resulted in a resonance condition right in the middle of the normal operating speed range, whereas Figure 15 shows a 'twisting' mode of the structure, with the front and back sides of the machine moving out of phase with each other.

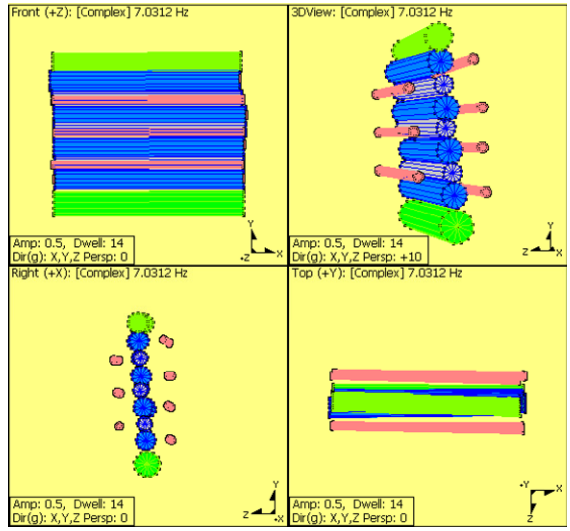

Figure 14. Machine Direction Mode Shape of the System

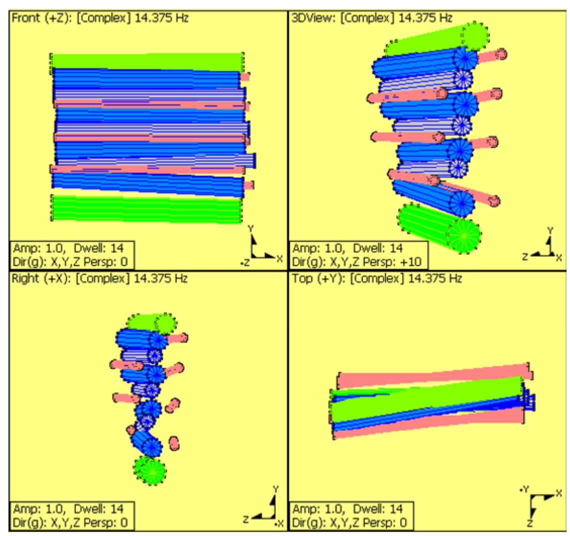

Figure 15. Front to Back Twist Mode Shape of the System

Impact Testing

Impact testing involves striking a point on a structure with a special hammer instrumented with a force sensor and measuring the response of the structure at different locations. Due to the mass and stiffness associated with paper machine frames, this form of testing is generally practical only on individual components such as rolls, mounting brackets, saveall pans, etc., as shown in Figure 16. For roll manufacturers, however, this is a very useful measurement tool to determine the response and damping characteristics associated with different roll materials, shell thicknesses and internal stiffeners.

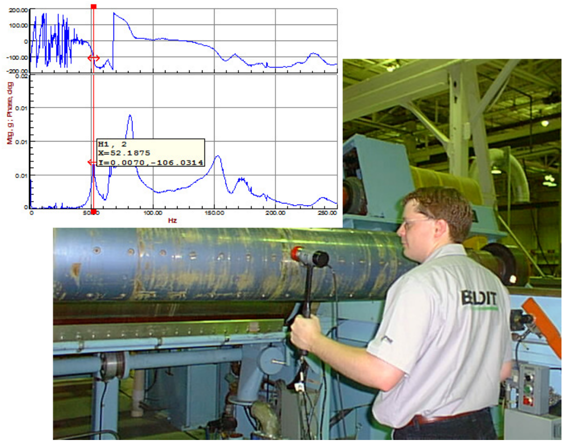

Figure 16. Impact Test on Paper Machine Roll

Other Roll Induced Phenomena

The most common causes of roll related vibration are:

- Unbalance
- Misalignment
- Looseness
- Excessive Runout
- Eccentricity
- Corrugation or Barring (this generally applies to nipped rolls)
- Bearing Defects
- Mechanical Drive Problems (Couplings, etc.)
- Electrical Drive Problems
- Resonance
- Cover Separation
- Deflection Variation

The measurements described in the earlier sections serve to quickly isolate problems associated with one or more rolls and the structural frames. The earlier a roll whose surface is developing a corrugated pattern is identified and taken out of operation for grinding and refinishing, the less material that needs to be removed [6]. Roll corrugation (also known as barring) is a phenomenon where the surface of the roll develops waves or bars that extend the length of the roll in the cross machine direction. In most cases, barring begins in localized section of the roll surface, either due to rolls being nipped together under pressure when the machine is not running or due to some foreign object passing through the nip during operation, resulting in a sudden deformation of the rolls surface. If the machine speed remains constant, then the barring eventually covers the rolls circumference, with the number of bars multiplied by the rotational frequency equalling the nip resonance frequency. This is illustrated in Figure 17.

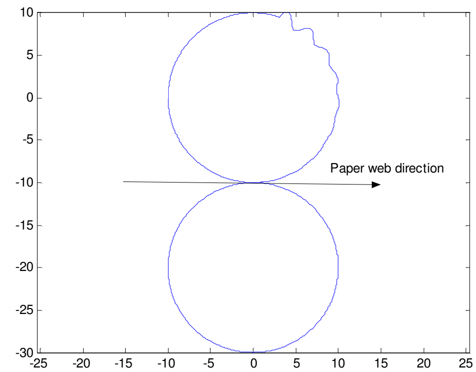

Figure 17. Development of Roll Corrugation

Variations in material characteristics of paper machine rolls can sometimes lead to a condition where the roll exhibits significant deflection variation (either under its own weight, or if external forces are applied). This was first proposed by Robert Alheid [6] following a series of calender and size press vibration problems in the early to mid 1990s, but even today, few manufacturers take this parameter into account for roll quality control. This deflection variation may also have some harmonic content (i.e., 1x, 2x, 3x, etc. of roll rotational frequency), which in turn can lead to vibration problems in machines as they provide the impetus for nipped rolls to bounce against one another. Allowed to progress for any significant length of time under steady state conditions, this bouncing gradually leads to more serious deformation of the roll surface and eventually, to barring.

Variations in roll construction come from various sources; casting and/or rolling/welding of the shells, machining and finishing, cover application, assembly and fitted bearings. There have been several advances in roll machining such as those presented by Widmaier; et al [7], but shell castings are still prone to problems, even though many suppliers have moved from poured castings to centrifugal castings.

Mechanical runout refers to a roll's deviation from a perfectly uniform radius as its circumference is traversed. One common tool to measure runout is a dial indicator, though most modern day roll inspection systems have sophisticated roll calipers for the measurement of runout. In theory, the measurement of runout should yield identical results no matter where on the circumference a dial indicator is placed. In practice, this is typically not the case, but in most cases this is only of academic interest. In some cases, however, the differences between horizontal and vertical runout are significant and can have catastrophic consequences when rolls exhibiting this phenomena are put into operation. In order to identify this deflection variation, a technique that is illustrated in Figures 18 and 19 is used. The process consists of setting two displacement transducers (in this case, LVDTs) at right angles to one another, so that they contact the exact same circumferential section on the surface of the roll face. Time synchronous averaging is then performed on the displacement data. In order to remove the contribution of the roll runout to the overall displacement data, the signals are shifted 90 degrees, relative to each other, and then the horizontal data is subtracted from the vertical data (or vice versa). This effectively removes the runout (which is the same no matter where it is measured on the roll), leaving only the deflection variation component.

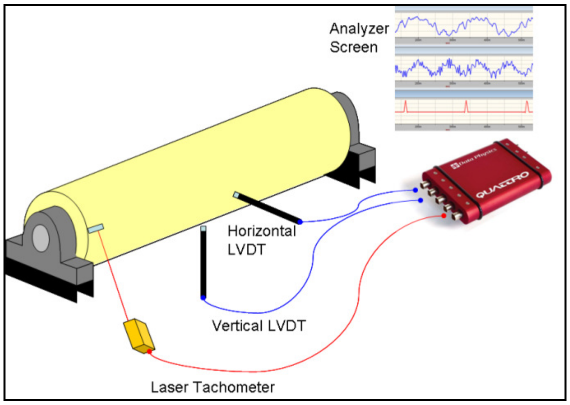

Figure 18. Test Setup for Roll Deflection Variation Measurement

Figure 19. Orthogonally Setup LVDTs Against Roll Surface

Figure 20 shows the two LVDT measurements with the 90° offset between them and Figures 21 and 22 show (with the help of simulated data) the difference between the case where no deflection variation exits and one where it does.

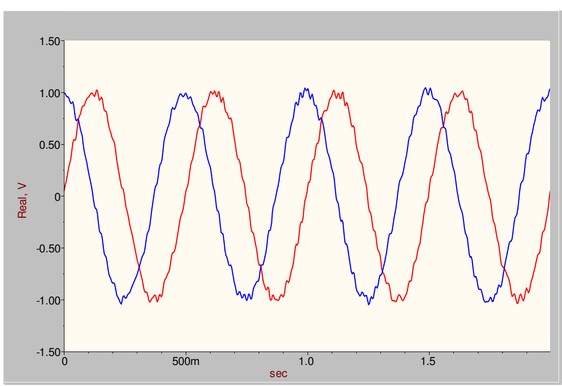

Figure 20. Horizontal and Vertical Measurements with 90° Offset between Signals

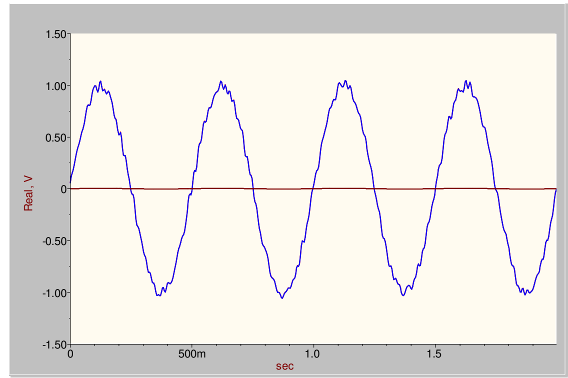

Figure 21. Result of H-V Calculation with no Deflection Variation Present

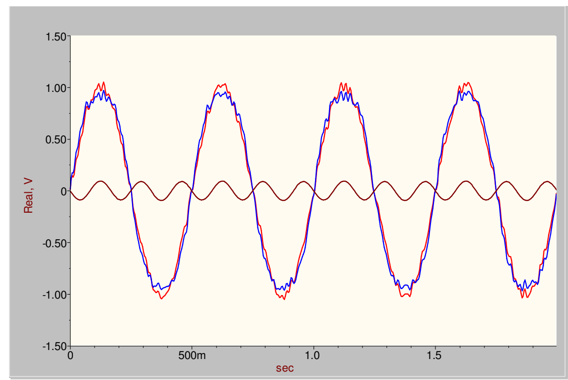

Figure 22. Result of H-V Calculation with some Deflection Variation Present

CONCLUSIONS

Recent advances in signal processing solutions for noise and vibration test applications make it necessary for industrial facilities to look beyond the typical but limited solutions of the past three decades. The key to successful diagnostics of supercalender stack vibration is simultaneous acquisition of vibration and roll speed data from every roll in the system and a comprehensive set of measurement functions that help isolate roll related and system natural frequencies. One aspect of the diagnostics, involving the electrical and mechanical drives and related torsional vibration has not been discussed and is the subject of work currently in progress.

Application of Acoustic measurements was not discussed in this study as the problem that the author was troubleshooting had more to do with reduced roll life and production interruptions. However, supercalender sections are notorious for excessive noise and Ambre [8] has done extensive work in thoroughly characterizing supercalender section noise. Using microphones, he has measured sound pressure levels across the face of the supercalender section and then calculated sound intensity values from microphones pairs measuring noise in a grid across the supercalender face.

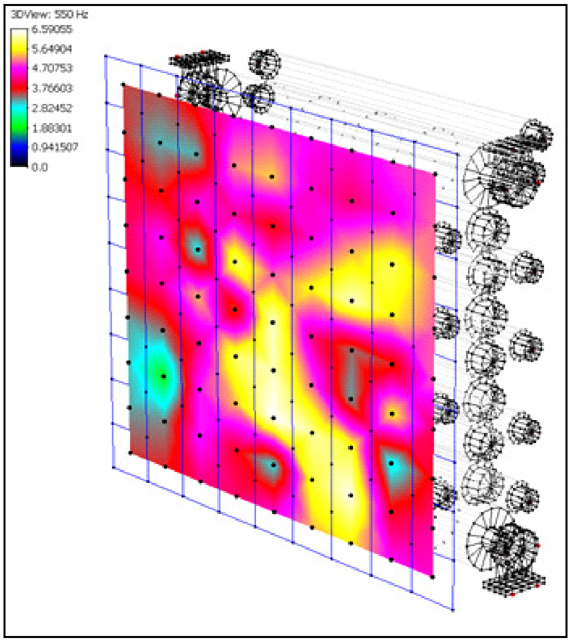

Figure 23. Sound Pressure Level Measurement Map Across Front Face of Supercalender Section

Figure 23 shows the sound pressure level distribution across the supercalender section and Figure 24 shows the sound intensity map for the same. This study was critical to correlating the audible energy with specific machinery component dynamics as well as noise source identification.

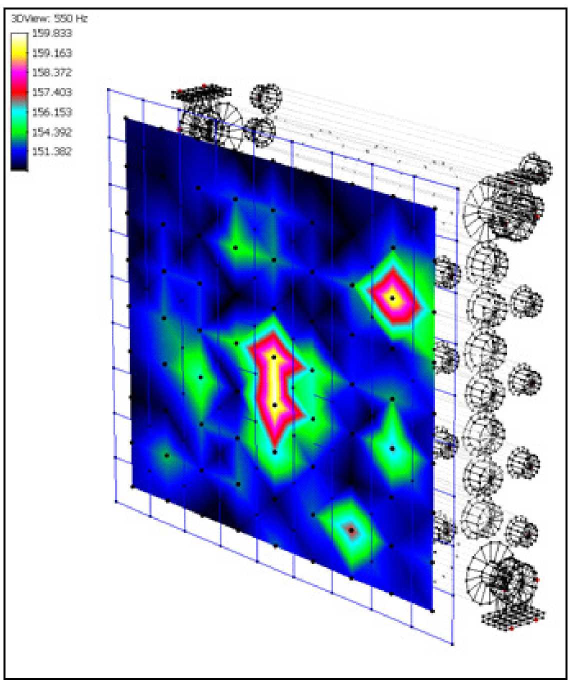

Figure 24. Sound Intensity Level Measurement Map Across Front Face of Supercalender Section

Further studies including combined vibroacoustic measurements are underway. A parametric study designed to evaluate optimum cover thickness, material and damping characteristics, as well as closed loop control of machine speed, nip loads, etc., relative to vibration levels are also being conducted presently.

Dynamic Signal Analyzers are needed to bridge the gap between portable data collectors and permanent monitoring systems. A channel count of 24-32 (or more) of vibration + multiple tachometer measurements is essential for a better understanding of the vibration issues on such systems.

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