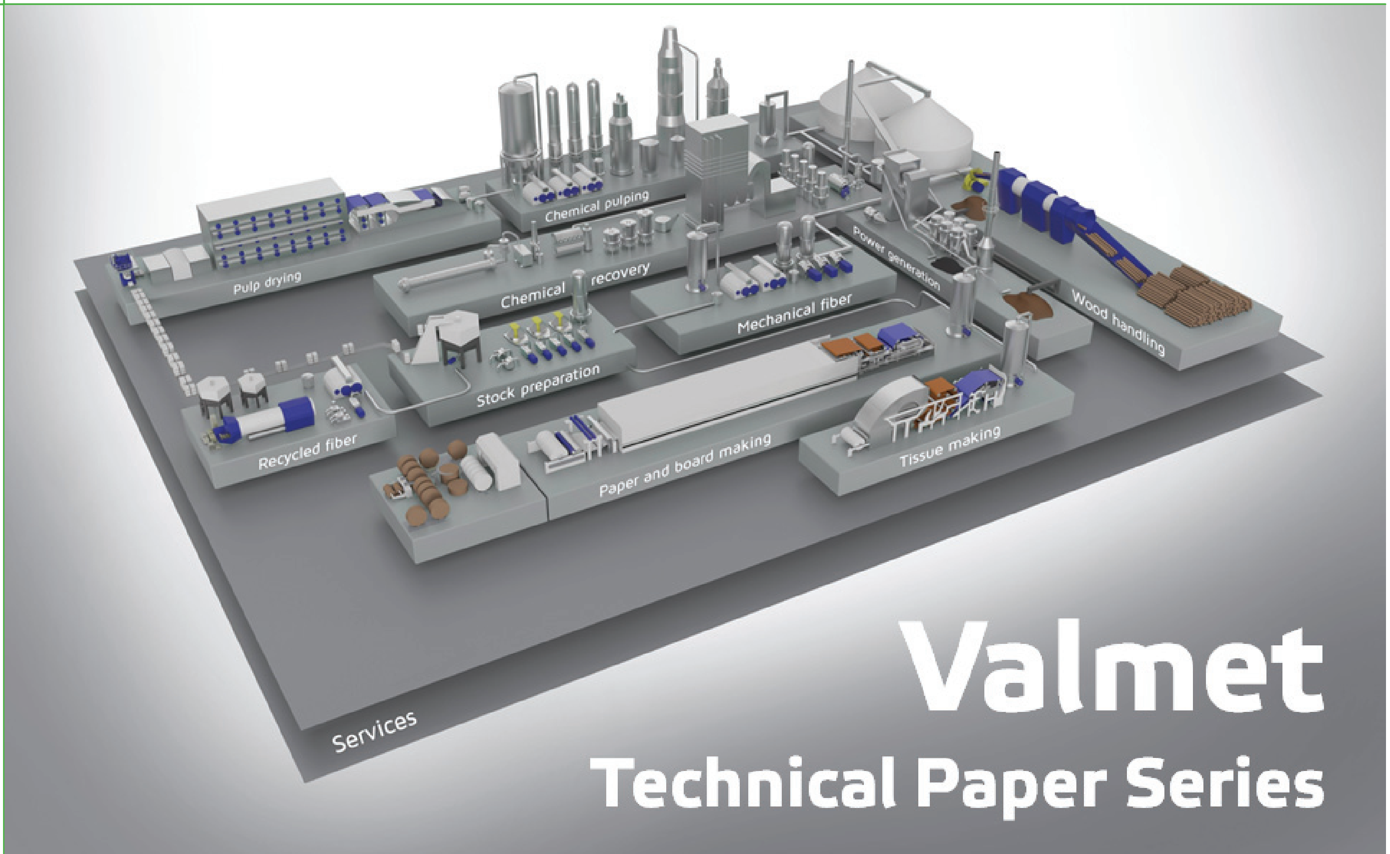

Vibration Analysis

Executive Summary

Vibration is increasingly becoming a problem as machine speeds have increased and paper quality requirements have risen along with increased competition. Balance grade G1 is requested and more time is spent on balancing the rolls in the machine. However, by balancing, mills typically measure only the MD vibration, especially with rigid assembled rolls (suction rolls, deflection compensated rolls, press rolls). Without measuring the vibration in all three directions, you don't know the exact contribution of the rotating rolls to paper machine vibration. This is why a complete vibration study must be performed.

Vibration analysis may be undertaken as a stand-alone process, or may be part of a machine section audit or comprehensive machine analysis. Regardless of the scope of the study, a similar process will be followed. The objective is established, a work plan is created, data is gathered using specific tools and sensors, and detailed analyses are carried out.

Skilled vibration analysts will look for tell-tale "signatures" – behavior and patterns that they have encountered time and time again. These signatures, similar to when a chess grand master views an in-progress chess board layout, will be instantly recognized as sources of vibration excitation. Thus a skilled vibration analyst is a highly valued member of any field service or mill maintenance team.

The mechanical dynamic behavior of a pulp, board, paper or tissue machine is a limiting factor for the machine's capacity. Vibrations in machine equipment constitute a safety hazard, and will cause severe problems in the paper making process and limit machine efficiency.

This paper will review what a vibration study consists of and why it's performed. It will also discuss the process of machine analysis by vibration study, and provide some examples of "vibration signatures" which Valmet vibration experts encounter in the field.

What is a vibration study?

A vibration study, as performed by Valmet, covers the mechanical condition and the dynamic behavior of the entire machine line from stock preparation to finishing, or of specific machine sections in troubleshooting. Both current production speeds and targeted speeds are studied. The cost of the study can be quickly recovered through subsequent savings on parts purchases, problem-solving, line speed up, and machine rebuilds. A vibration study may also be included as part of a larger scope Machine Analysis.

Objective

The main objectives when performing a vibration study typically fall into one or more of three categories:

- **Capacity** - map the dynamic behavior of the machine from current to targeted speeds, yielding the most cost effective approach by foreseeing problems.
- **Rebuild** - evaluate how rebuilds will affect the dynamic behavior of the machine and its consequences at current or increased speeds.
- **Troubleshooting** - locate and eliminate vibration sources currently having a detrimental effect on the machinery or process.

Figure 1. Vibration analysis requires skilled expertise.

From Valmet's perspective, each objective is based on extensive paper machine building expertise, utilizing top of the line hardware and software for analysis. Measurements and investigations are carried out during production and at a machine shutdown. Valmet's vibration studies combine mathematical analyses and diagnostic measurements in a distinct aim to make your machine run smoother, faster and more cost efficiently.

Benefits

A vibration study will typically yield the following benefits:

- Determination of the dynamic behavior of machine sections
- Determination of the mechanical condition of the machine
- Determination of the feasibility of a possible capacity increase
- Most cost-effective implementation of rebuilds
- Prediction of future mechanical problems and reduction of unplanned shutdowns
- Scheduling of service actions based on prioritized maintenance recommendations

- Savings on roll rebuilds by relocating old rolls to positions where they can still be used
- Solutions to problems such as barring and gear train failures

Measurements and design review

Measurements taken during production include:

- Mechanical condition measurement (e.g. vibration, dynamic run-out, etc)
- Synchronized measurements
- Operating deflection shape measurements
- Paper samples
- Noise level measurements (where applicable)

Figure 2. Specialized tools and sensors are used during vibration analysis.

The following measurements are performed during a machine shutdown:

- Speed tests
- Impact tests and modal analyses
- Run-out measurements
- Synchronized measurements

A vibration study also includes dimensioning reviews and mathematical analyses of line components and structures.

Reporting of findings

Valmet's vibration study reports are clear and comprehensive. They include an explanation of all measurements and reviews conducted. The mechanical and dynamic behavior of each component analyzed on each machine section is covered. Recommended actions are also detailed for each component. These will improve the reliability and availability of the items analyzed. A vibration study reduces maintenance and shutdown costs and cuts down the probability of unanticipated shutdowns.

Each report is accompanied by an electronic database that can be used to prioritize and manage the recommended actions.

Expertise and Measuring Equipment

All Valmet experts possess extensive mill experience and the latest equipment expertise. They make use of specialized tools and tested approaches developed over decades at hundreds of customer mills. Valmet's vibration studies combine mathematical analyses and diagnostic measurements in a manner that helps to produce tangible savings in connection with line upgrades and reduces related risks. Our expertise is built on Valmet's extensive engineering experience and know-how.

How is a vibration study performed?

Vibration analysis is a core component of most Reliability Centered Maintenance programs, and it is here we continue to meet that same age-old question – How long will a piece of equipment last? Indeed, this issue becomes ever more pressing with increased competition requiring the highest effective utilization and efficiency levels of the paper machine.

Raw time waveform analysis

Machine analysis and vibration study personnel will use the measurement of a variety of signals to help determine the nature and source of a problem. The most common measurement is that of vibration - in units of acceleration, velocity or displacement. Other signals may include pressure or sheet quality parameters, such as basis weight, moisture and caliper.

Analysis of the raw time waveform provides valuable information for the troubleshooting of many problems, including those with gearboxes. Impulsive vibration (due to problems with gear tooth contact, etc.) is better analyzed in the time domain.

The most fundamental form of analysis of these signals is the time domain. This form of analysis allows the analyst to see the amplitude of the signal (peak to peak) versus time. By adjusting the sampling rate, and the length of the time record, the analyst can establish many physical characteristics of the signal and machine under test. It is often a very underutilized method of analysis.

Time domain analysis is very good for analyzing non-deterministic signals such as random or impulsive signals generated by defective gears, barring or beating.

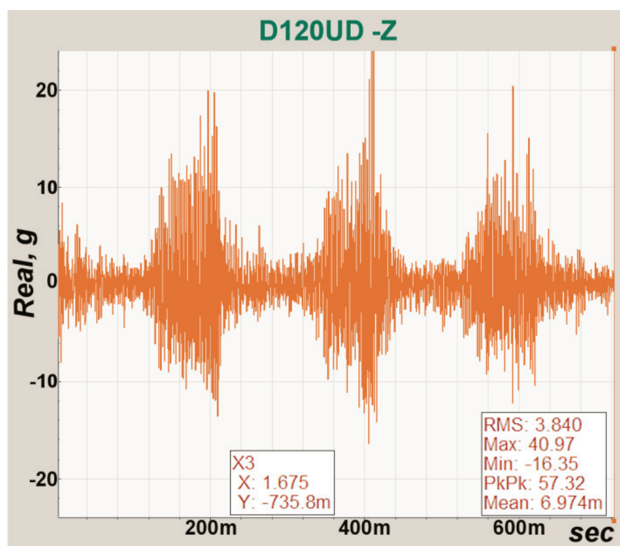

Figure 3. Analysis of the raw time waveform provides valuable information for troubleshooting many problems. The figure shows the amplitude modulation of the gear time waveform due to axial run-out of the gears.

Spectrum Analysis

Spectrum analysis separates the total vibration into discrete frequencies so that the source(s) of a given problem may be easily identified. Spectrum analysis involves passing the raw time domain data through a mathematical calculation called the Fast Fourier Transform or FFT. The FFT algorithm converts the original signal from the time domain into the frequency domain. The result is that a complex signal is separated out into different contributing frequencies (units of Frequency are cycles per unit of time, e.g., Hertz = cycles/second).

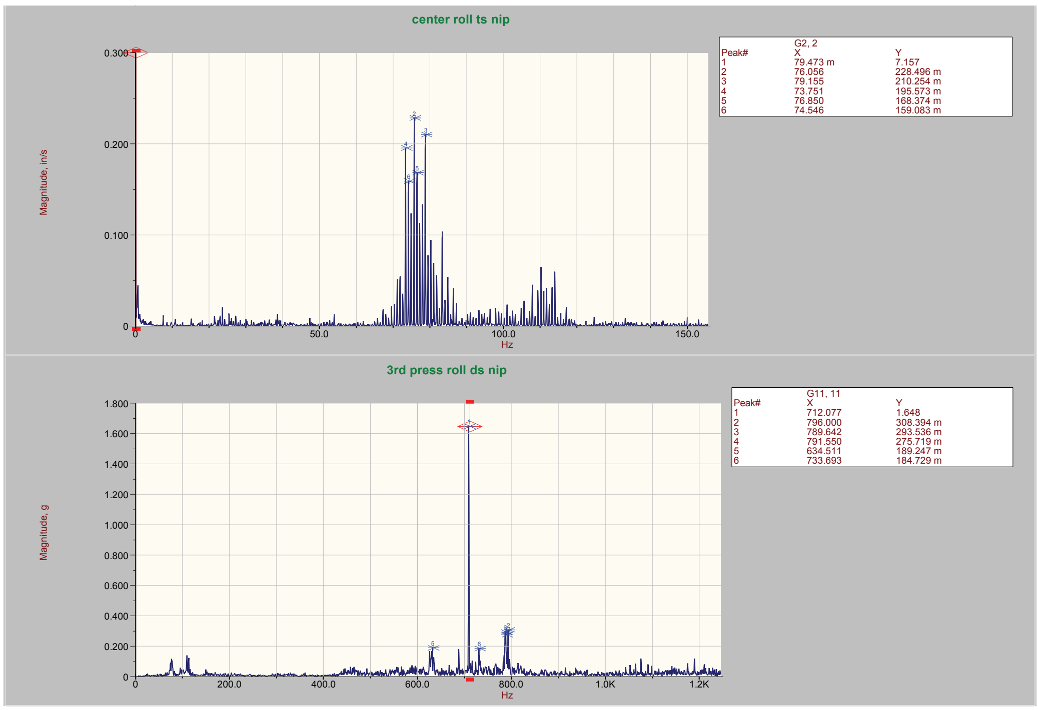

Figure 4. The same signal may need to be analyzed over different frequency ranges.

It is important that the same signal is analyzed over different frequency ranges for a complete understanding of the problem. Experience and good data acquisition skills and tools are essential for making sure that all relevant frequency ranges are verified. A common mistake analysts make is to analyze all data over a single frequency range.

Resolution implies the ability to distinguish between closely spaced frequencies. Too little resolution causes the analyst to assume that a single frequency or source of interest exists - when several frequencies and therefore, several sources may actually be present, but very close together in the frequency domain.

Flexibility in being able to display a lot of data simultaneously allows for effective diagnostics. The Valmet data analysis and acquisition system has very advanced data presentation tools. Multiple signals can be easily overlaid for quick comparison and source identification. This allows simultaneous determination of vibration severity and contributing sources can be analyzed at different locations.

Tachometer signals from various rolls, felts, etc. allow for precise source identification. In the example shown in Figure 5, the green trace shows a spectrum generated by a tachometer signal on a CC roll, so that fundamental and multiples of rotational frequency can be known easily. It is presented in the frequency domain so that vibration frequencies may be compared to it.

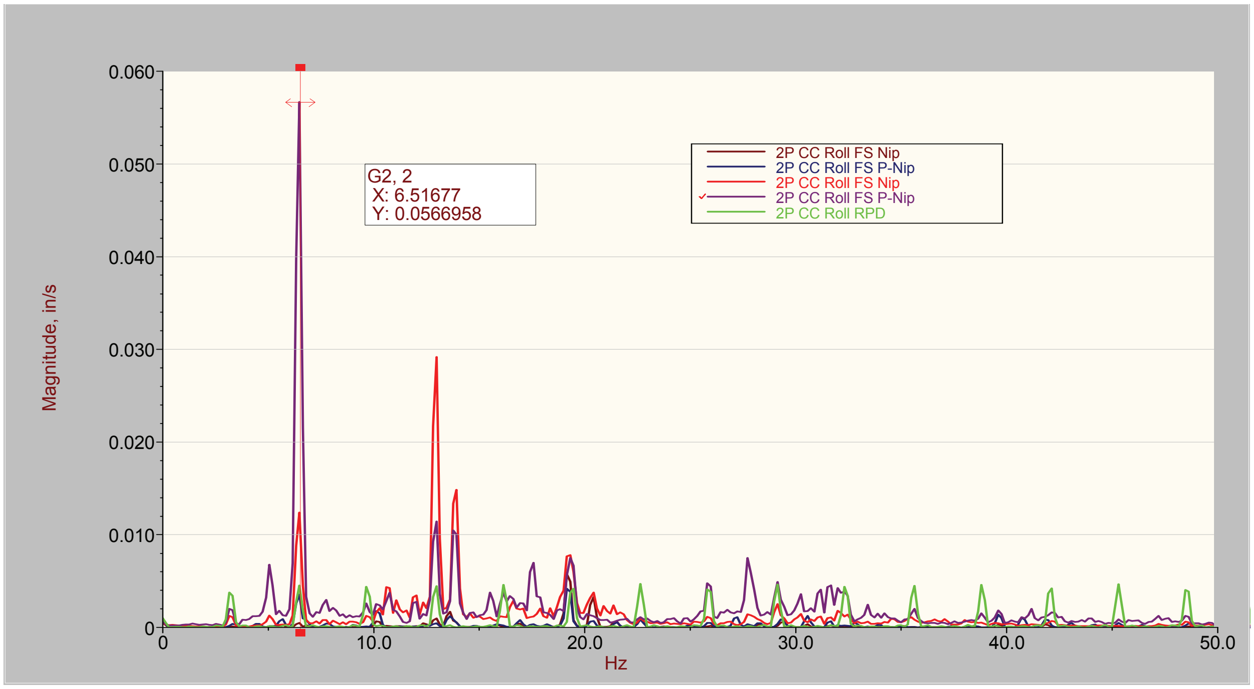

Figure 5. Multiple signals can be compared simultaneously so that vibration severity and contributing sources can be analyzed at different locations.

Speed Trials

Changes in vibration levels as a function of changing machine speeds or loads are normally analyzed using waterfall plots. Waterfalls, also referred to as cascade plots or spectral maps, consist of a series of spectrums placed one behind the other to generate a 3-dimensional graph. The X-axis represents Frequency, the Y-axis represents vibration amplitude and the Z-axis represents time or machine speed. Waterfalls are useful for the identification of resonances. The high energy levels of the rotating components excite structural resonances, as well as those of rolls and major components.

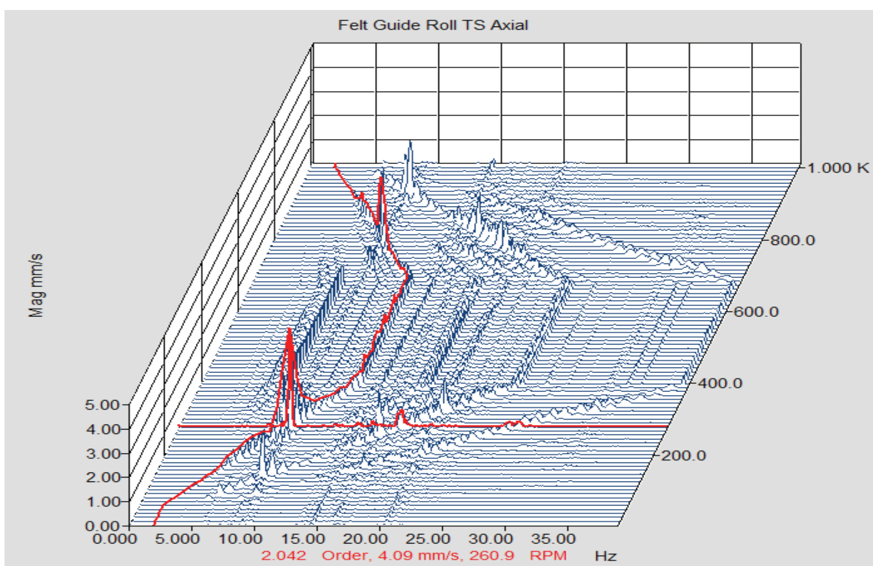

Figure 6. Changes in vibration as a function of changing machine speed are easily analyzed with waterfall displays.

Changes in vibration as a function of changing machine speed are easily analyzed with this tool. In the example shown in Figure 6, the red trace shows a particular order or multiple of the roll being tached. A clear resonance is seen peaking at 260 rpm.

Impact Testing

The purpose of impact testing is to identify the natural frequencies of typically smaller components in the machine, such as tube rolls, doctors, drive shafts, motor stands, showers, uhle boxes, etc. This complements the speed trial, because the speed trial and resultant waterfalls will show multiple excited natural frequencies. The next challenge for the analyst is to determine which component was actually resonating, because the waterfall shows them all.

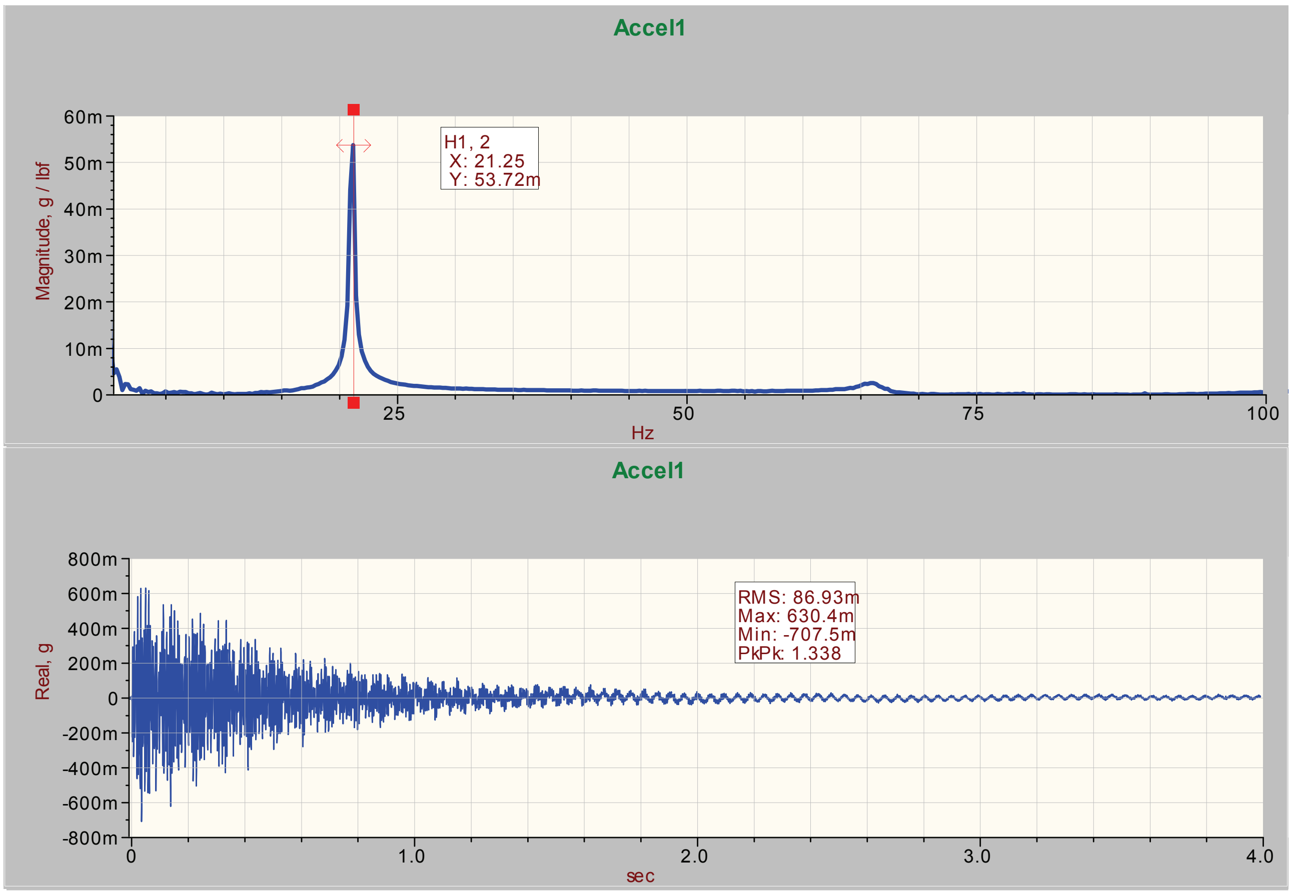

Figure 7. In these impact testing graphs, the top chart shows the time domain response while the bottom chart is the transfer function, i.e. ratio of response to impact force.

The equipment consists of a modal hammer that contains a force sensor, and a conventional vibration sensor such as an accelerometer mounted on the component being measured. The component is impacted by the hammer, which measures the force of impact. The accelerometer measures the response. The software then generates a transfer function in the frequency domain - the ratio of response to force. The peaks of the transfer function correspond to the natural frequencies of the component being measured. The amplitude tells the analyst the energy required to excite the mode (natural frequency).

Synchronous Averaging

Synchronous averaging is used to isolate the contribution of vibration of a single rotating source. This is done by obtaining a tachometer trigger from a given roll or felt and then timing the data acquisition perfectly with the occurrence of the trigger. Averaging of a series of acquisitions then removes the vibration contribution of asynchronous components - leaving only that vibration which is synchronous with the trigger.

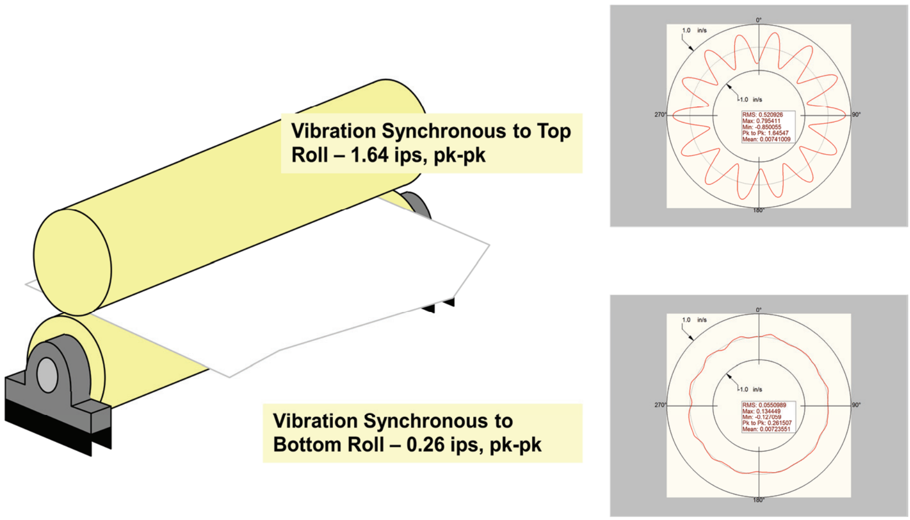

Figure 8. Synchronous Averaging – Paper machine calender before problem correction.

Figure 8 shows synchronously averaged vibration in polar run out format measured on the bearing housing of the bottom roll. The top roll is the dominant contributor to the vibration in the calender nip. Both graphs represent vibration measured with the same transducer or sensor, but different tachometer trigger sources.

The vibration synchronous to the top roll had a peak to peak vibration level of 1.64 inches/second (ips), which was very high. The vibration synchronous with the bottom roll was only 0.26 ips, peak to peak, in comparison. The top roll shows 14 well developed bars or corrugations, while the bottom roll shows 12 low amplitude bars.

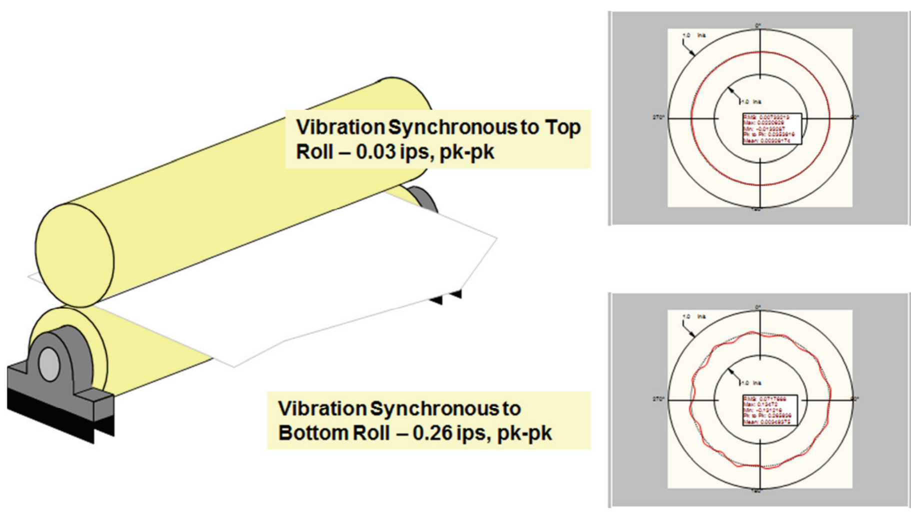

Figure 9. Synchronous Averaging – Paper machine calender after problem correction.

It was recommended that the top roll be replaced immediately. Following replacement of the top roll, new data was acquired (Figure 9).

The new data shows that the vibration due to the top roll had reduced to 0.03 ips, which was well below acceptable levels. The bottom roll, which was not changed, still showed a contribution to the nip vibration of 0.26 ips. The 12 bars are still evident from the polar run out plot. The polar format provides a very powerful visual tool particularly when combined with the synchronous averaging capabilities of the analyzer.

When barring is a long term problem, the system and history need to be reviewed from problem inception through to present day symptoms. Barring is one of the most difficult issues to resolve from an analysts' standpoint, especially on the wet end of the machine. In the case of machine calender barring, one remedy is to slightly offset the rolls in a machine calender stack according to careful measurements and calculations.

Operating Deflection Shape (ODS) Analysis

ODS analysis shows how a machine or structure moves in actual operation at specific frequencies of interest and helps determine the cause of the motion. Frequencies used in the analysis are usually multiples of running speed of the various rolls in the system, gear mesh frequencies, etc.

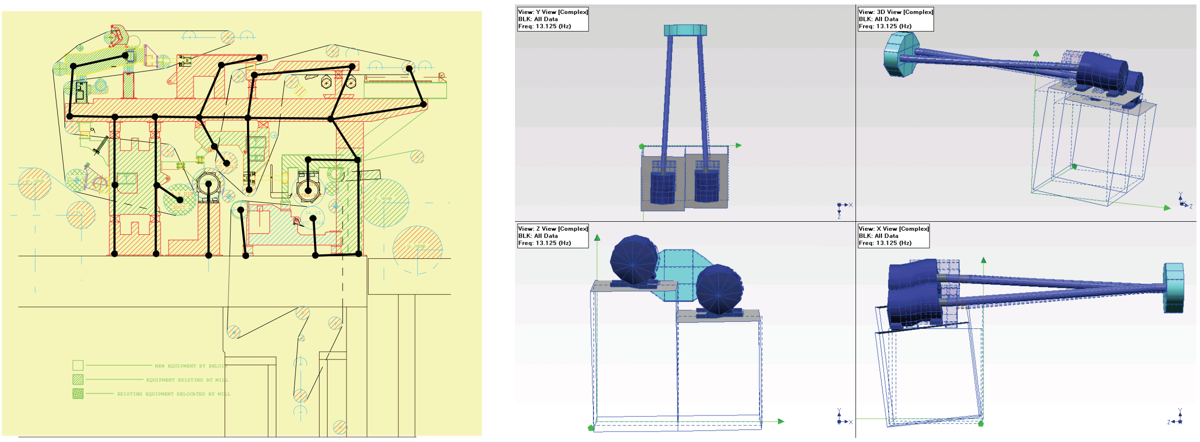

Figure 10. ODS analysis helps to understand how a paper machine moves during operation. (Left, Twinver plus third press; Right, drive train in 3D)

If the data used in the ODS analysis is fit to natural frequencies of the system (identified in speed trials, etc.) then the resultant model will show mode shapes instead. Knowing which modes are being excited and the positions of greatest movement allow for the most effective structural modifications.

An ODS requires gathering vibration data (under normal operating conditions) in three directions at various points on a machine (framework, rolls, etc.). The data is then processed on a personal computer to allow animation of a stick figure or 3D model representation, showing relative amplitude and phase between all measured points, at any selected frequency.

The pictures in Figure 11 are single frame shots from a movie that shows the motion of a press section at a 5 Hz natural frequency. The 5 Hz frequency was identified during speed trials. The software can allow easy visualization from ANY angle of interest.

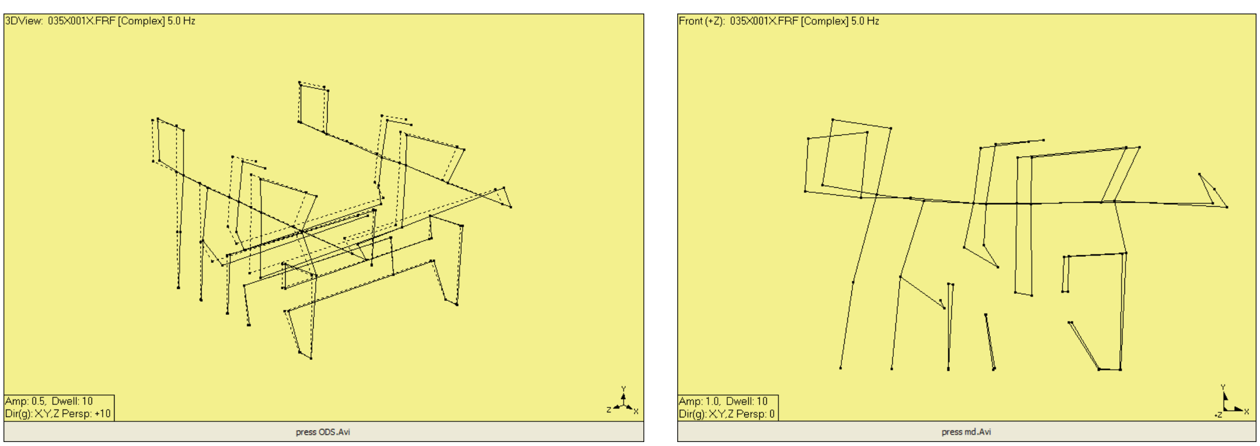

Figure 11. ODS animation software uses the machine model and measured information to display machine movement at desired frequencies.

Finite Element Analysis

Finite Element Analysis (FEA) involves the mathematical modeling of a physical system to predict the structural behavior of the system - involving geometry, material properties, boundary conditions, etc.

The model is used to determine what the new natural frequencies of the system will be after structural modification is applied. The model can be as simple or extensive as required.

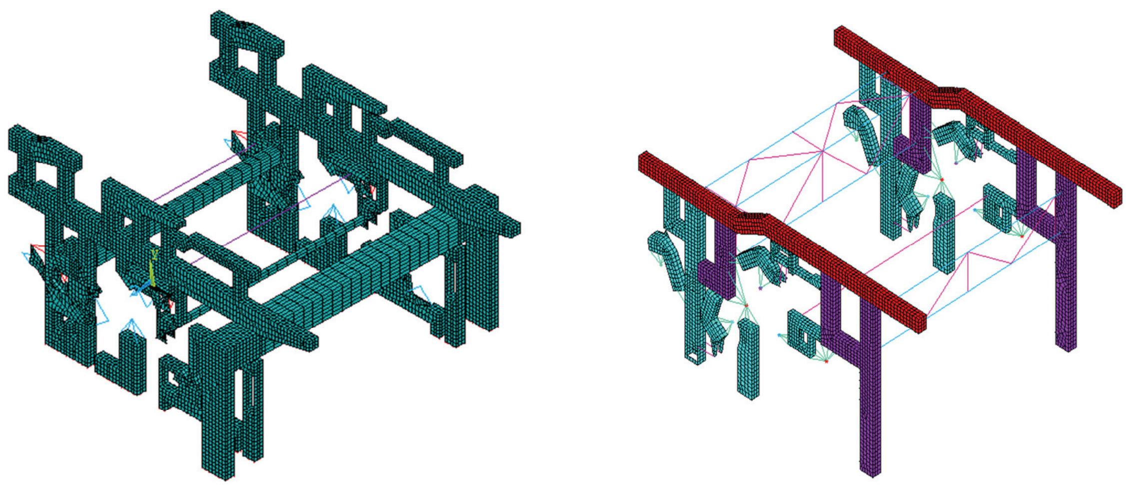

Figure 12. FEA models such as these shown for press sections can be extremely detailed or fairly simple, as needed by the current analysis

In cases where a machine does not have sufficient drive capacity to perform speed trials up to the targeted speed, FEA can be used to predict the response at these higher speeds. The ODS model (shown earlier) is used to fine tune the accuracy of the base model.

The Importance of Vibration Signatures

One thing is certain, the moment an asset is placed in service, it is headed towards failure. It is the vibration analyst, armed with analyzer, accelerometers, strobes, charts and plots who must shoulder the daunting task of predicting and preventing premature failures, which lead to costly downtime.

Success depends on the analyst's proficiency in recognizing how the most common equipment maladies manifest in the FFT and time domain plots. Following is a brief discussion of a few "vibration signatures" Valmet has discovered during diagnostic analysis.

Unbalance

There is always some unbalance present in rotating elements. Typically every mill has a prevailing quality of balance specification to which they adhere in order that resulting vibration be minimized. Any unbalance can be broken down into pure static and pure couple unbalance. It usually results in a high radial 1X rotational frequency peak in FFT (figure 13). In overhung equipment it can further give rise to a high 1X axial peak. In time domain plots, it is one malady that mimics closely the oft-used training aid - the sine wave.

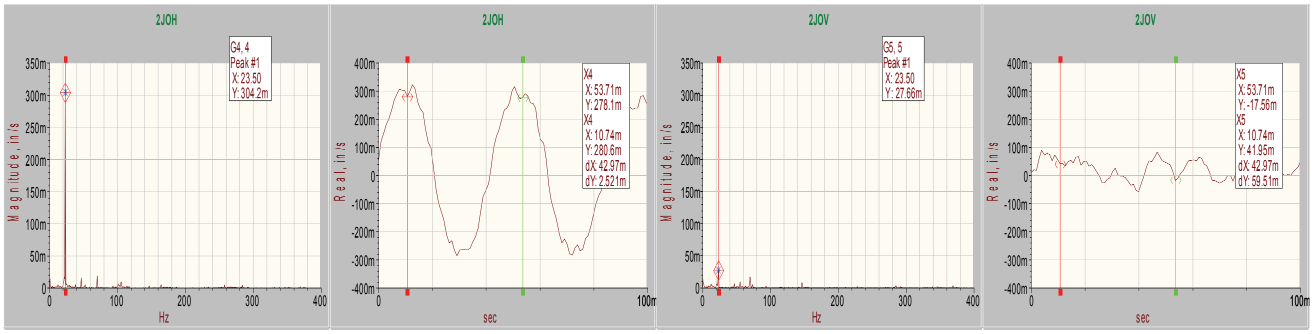

Figure 13. Unbalance due to a driveshaft required investigation in both the vertical and horizontal planes.

It must be understood that structural stiffness can differ significantly between the horizontal and vertical planes. In this particular case, the nature of the problem could easily have been overlooked had only the vertical plane been chosen for radial measurement. The horizontal amplitude was 10X higher than vertical. This problem turned out to be a grossly unbalanced driveshaft, and the online system did not pick it up because only the axial plane was measured.

Misalignment

Types of misalignment include offset, angular, and the combination of the two. More often than not, misalignment is combination. Angular misalignment can create high 1X and 2X peaks in the axial direction and can be 180 degrees out of phase across the coupling. Offset misalignment also creates 1X and 2X peaks, however it usually shows up in the radial direction. The 2X can often exceed the 1X component. The time domain can take on a pronounced W pattern. Figure 14 shows examples of combination misalignment of a press drive train.

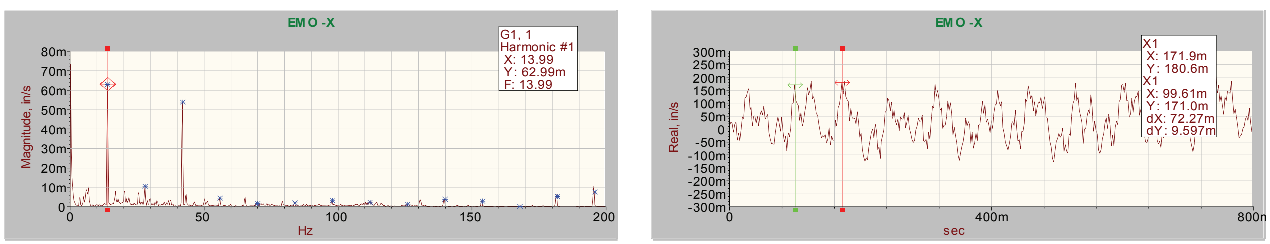

Figure 14. Combination misalignment of a press drive train.

Impacting

Impacting can occur with bearing damage or in the presence of structural interference. It can be synchronous or non-synchronous to turning speed. Any significant impacts will always excite surrounding structural resonant frequencies. Therefore the pattern can usually be readily seen in the time

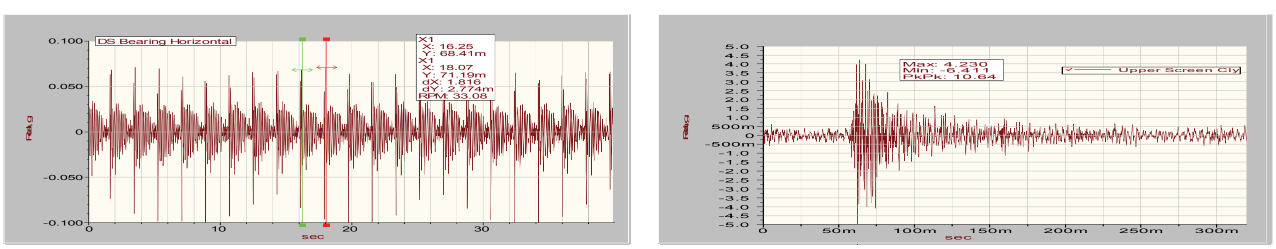

Figure 15. Examples of captured impacts. (Left, suction roll; Right, primary screen)

domain. The impact will have an immediate and sharp rise followed by a ringing down; similar to a pattern expected when ringing a bell.

Figure 15 shows two examples of captured impacts. The left plot is of a suction press roll that had internal interference of the suction box and was impacting 1X/rev. The right plot was measured on a primary screen that was being operated above its hydraulic capacity resulting in intermittent deformation of the basket creating internal interference.

Looseness

Looseness can result from wear, cracked welds, loose/broken fasteners, excessive bearing clearance, or improper fits. It can often be seen in the FFT wherein multiple harmonics of turning speed exist. This author has seen as many as 100 harmonics on occasion. Often the amplitudes are fairly low; however, the fact of their existence often portends some underlying problem that will only get worse with time. The higher order harmonics can sometimes become forcing functions that excite otherwise benign resonant frequencies.

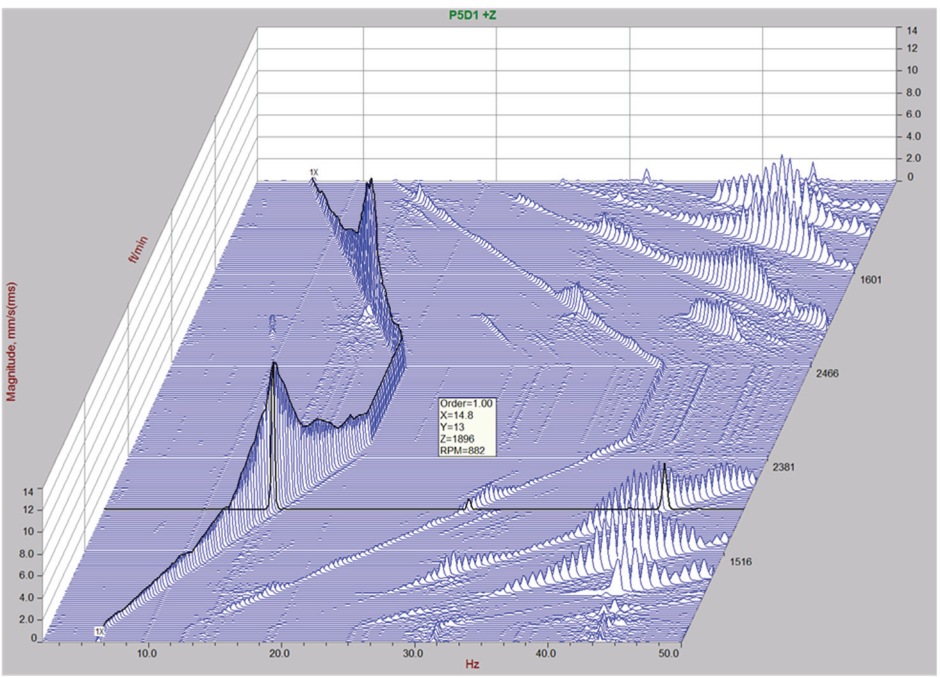

Figure 16. Example FFT waterfall showing clear peaks.

Resonance

All structures have multiple resonant frequencies. OEMs attempt to design machinery in such a manner as to place harmful structural resonant frequencies well away from rotational frequencies. The general trend is to push the paper machine faster and faster to increase production output. At some point this pushes the 1X and 2X rotational frequencies well into areas of potentially harmful resonant frequencies; often with catastrophic affects. The residual unbalance and misalignment of rolls and drive trains create an excellent in-situ shaker if the 1X or 2X rotational becomes near or coincident with a structural resonant frequency. This same shaker effect can be used to our advantage to help find areas of resonance by executing ramp tests prior to any implemented production speed increases. The data is acquired during ramp of contiguous machine sections during controlled acceleration and then deceleration. The speed range should cover the highest anticipated target speeds. Figure 16 is a waterfall FFT of such a test. This waterfall is a succession of FFTs in a single multi-axis plot. The axes are X (frequency), Y (amplitude) and Z (time). It can become clear quickly at what speeds might cause problems.

Summary

This article has only presented the tip of the iceberg of vibration analyses. Yet we hope that it has provided a brief glimpse into the analyst's world. At the very least, we trust you are reassured that there is a certain rationale to the vibration analyst's rapt glassy-eyed attention to hundreds of vibration signatures every day. After all, someone has to answer the question, "How long will it run before it breaks?" Whether it's Valmet personnel or your own mill vibration analysts - their job is difficult, requires specialized training and tools, and is frequently underappreciated.

This white paper combines technical information obtained from Valmet personnel and published Valmet articles and papers.

Valmet provides competitive technologies and services to the pulp, energy and paper industries. Valmet's pulp, paper and power professionals specialize in processes, machinery, equipment, services, paper machine clothing and filter fabrics. Our offering and experience cover the entire process life cycle including new production lines, rebuilds and services.

We are committed to moving our customers' performance forward.