Vibration analysis is the cornerstone of predictive and preventive maintenance

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Vibration analysis is the cornerstone of many predictive and preventive maintenance programs.

Analyzing vibration signals transmitted from rotating equipment is the cornerstone of many predictive maintenance programs. Studying these signals can be of great assistance in determining the operating condition of equipment and the nature of a problem if one exists.

In this paper, we'll summarize vibration analysis theory and applications for the pulp and paper industry. There are a wide variety of methods and opinions on how to perform vibration analysis effectively.

Basic vibration operations

Mechanical equipment will oscillate in reaction to excitations or forces. The amount of vibration present depends on the amount of excitation present, the equipment's mass, stiffness, and how much damping is present.

For vibration to be interpreted, it must be transformed into a signal that can be analyzed. Mechanical motion from a piece of machinery can be sensed by a vibration transducer and converted into an electrical signal which can be amplified, displayed, and analyzed. There are various types of transducers. The three main types are displacement probes, velocimeters, and accelerometers.

A displacement probe, sometimes called a proximity probe, measures the movement of a conducting surface relative to the probe. These probes are commonly used on large, expensive machinery such as turbine-generators and compressors. Their main advantage is that they actually measure the movement of a rotor. The main disadvantages of these probes are that they are stationary and expensive per individual measurement point.

A velocimeter measures how fast the machinery is moving. It is a self-generating device that is used for many portable applications. It is made up of an enclosed coil with a movable, permanent magnetic core. The relative motion between them causes a voltage change. The velocimeter's main disadvantages are that the probe can be large in size, cannot directly measure shaft position, and below 600 cycles/min the signal is severely attenuated.

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An accelerometer consists of a piezoelectric crystal that produces an electrical signal when it is stressed. This signal is proportional to the rate of acceleration that the machinery experiences. Accelerometers are the most common type of probe used for portable vibration analysis units. They are relatively small and can be sensitive to a wide frequency range. Their main disadvantages are that mounting arrangements are critical, they are susceptible to field damage, and they are relatively expensive.

The electrical vibration signal from the vibration probe is transferred to some form of vibration analyzer. There are various forms of analyzers. They range from simple hand-held units that give only a numerical measure of how much vibration is present to units that analyze the signal in great detail. About 10 years ago, dedicated real-time analyzers began to be used commonly. They take the electrical signal from the vibration probe and continuously transform a time-domain signal (amplitude vs. time) into its frequency-domain spectral components (amplitude vs. frequency). This is also referred to as a spectrum. By being able to break down the signal and identify the frequencies present, the individual sources of vibration can be determined. This is performed by Fourier analysis. Fourier analysis takes any unique waveform and transforms it into the sum of individual sine waves.

A real-time analyzer is capable of taking a signal from either a displacement, velocity, or acceleration probe. The analyzer can then integrate or differentiate the signal so that it can be displayed as either displacement, velocity, or acceleration from any of these probes.

With only a real-time analyzer, a cable with necessary connections, and an assortment of vibration transducers, most machinery vibration problems can be solved.

Analysis format

Some mills obtain overall vibration readings for the equipment that they survey. The overall vibration level is a measurement of the total energy associated with all of the vibration frequencies coming from a given measurement point. With these readings, they trend the numbers to determine if there is an increase and if any overall vibration readings are above a predescribed alarm limit. This process has the advantage of being very easy to understand and of being able to analyze a considerable amount of equipment in a short period of time. In addition, some mills will then use a real-time analyzer to further analyze equipment with high vibration levels.

Other mills will collect the vibration data on a tape recorder and then play this back into a real-time analyzer. This has the advantage of analyzing the signal in more detail and allows the signal to be replayed numerous times for analysis. The disadvantage is that it is very time consuming.

Some mills take their dedicated real-time analyzers into the field. This allows direct readings to be analyzed with the greatest flexibility at the equipment location, but because they are portable and more difficult to use, few readings can be taken per unit time.

During the last several years, mills have begun to use computer-based data collection systems. The computer software creates a database which defines each point to be checked and fits it into a survey format. These surveys are loaded onto electronic data collectors so that vibration readings can be taken in the field. After the route is complete, the readings are downloaded back onto the computer for analysis.

A fast computer is required because you can easily be overwhelmed with data. Most importantly, you need a software system that is fast and easy to use.

The data collectors are improving, and some are beginning to rival the dedicated real-time analyzers. They offer several advantages over real-time analyzers and tape recorders:

- Just about any survey can be performed by one person.
- They are easier and faster to use due to their portability and menu-driven setups and database.
- They organize the equipment to be surveyed into a route format.
- They can lessen the response time to a request to spot check a piece of equipment.

Resonance

The natural frequency of any object is the frequency that it would vibrate at if it was struck a blow. The natural frequency increases with increased system stiffness and decreases with increased system mass.

When an excitation to an object is vibrating at the same frequency as the object's natural frequency, then a state of resonance occurs. At this point, the object will have a much greater relative amount of vibration. This is also called the object's first critical. An object also has higher frequencies at which it will resonate. These are called second critical, third critical, and so on.

The mode shape is the dynamic shape of an object at a natural frequency. Nodes are the points on an object that do not move when excited by a natural frequency. Antinodes are the positions of maximum movement when excited by a natural frequency. This information can be essential to help determine where to alter an object's mass or stiffness to reduce excessive vibration problems.

Beating

Beating occurs when two pieces of equipment operate in close proximity to each other at similar operating speeds. Their vibrations go in and out of phase with each other in a sinusoidal manner as a result of differences in their rotational speeds. Beating can be significant when the vibration signals align with each other.

Imbalance problems

Imbalance in rotating equipment is characterized by being sinusoidal at a frequency of once per revolution and an amplitude that will increase with speed. Imbalance forces increase with the square of the rotating equipment's speed.

When balancing corrections are made, a key-phaser is utilized as a means to reference shaft rotation with respect to phase and vibration amplitude.

Rotating machinery parts that are repaired or manufactured should be balanced before leaving the machine shop. Newer balancing equipment with built-in software makes balancing more accurate and faster.

Misalignment

Vibration due to misalignment is usually characterized by a predominant two-times-running-speed frequency component and high axial readings. Often harmonics of two times the running speed will be present. Relative phase readings can help determine if misalignment is a problem. Axial vibration at each end of a machine will be approximately 180 degrees out of phase from each other.

Mechanical looseness

Mechanical looseness is characterized by a large number of running-speed harmonics in the frequency spectrum. Looseness tends to produce vibration that is directional, and therefore the time-domain signal will probably be truncated. Readings can be taken at various positions on the machinery to help detect this problem.

Fluid-film bearings

A fluid-film bearing that is damaged will experience a great deal of instability. This is due to a pressure differential in the direction of rotation causing an oil whirl to occur. This vibration will be present at slightly less than one-half times the running speed. This oil whirl may be constantly changing speed and amplitude.

Pump vane pass

A pump that is not operating on its designed pump curve will emit a vane pass frequency equal to the number of vanes times the running speed. Usually several harmonics of this frequency will be present.

Gear reducers

Gear problems are characterized by vibration spectrums that typically are easy to recognize but difficult to interpret. Comparisons of vibration spectrums to baseline vibration spectrums is helpful because high-amplitude frequency components are common even in some new gearboxes. Identifying new components in the vibration spectrum, or components whose levels have changed significantly, is important. A gear-mesh frequency will be emitted by almost all gear sets. It will be equal to the number of teeth on a gear mesh times its rotational speed. The amplitude can vary with load. Sidebands of various gear's running speeds can be used to indicate where a problem may exist.

Electric motors

When the rotor is not aligned properly within the stator, an uneven air gap occurs. This can produce a vibration at 120 Hz.

Motors under load that have damaged rotor bars will experience a high vibration at once-per-revolution frequency. Close examination of this frequency may reveal that it is constantly changing speed and amplitude.

Another indication of electrical problems is when the slip frequency's amplitude is within at least 40 db of the line frequency's amplitude. This can be checked with a clamp-type amp probe around the electrical leads.

Synchronous averaging

Different sections of a paper machine, especially the press section, can be analyzed by synchronous averaging. This is a process of determining the effects of one rotating piece of equipment on another. It is the averaging together of different time-domain waveforms and developing a resultant frequency-domain spectrum.

An example of this is to place vibration probes on two separate press rolls and connecting them to a two-channel analyzer. The analyzer can then be triggered from one of the rolls by a phototach. This synchronous averaging takes away the contributions of the roll being used as a trigger.

By placing probes on various rolls in a press section and moving a trigger from place to place, the cause or causes of vibration can be isolated. If a large number of averages are taken, any vibration that is not in synchronization with a particular roll will appear as noise and average out. Problems such as an out-of-balance roll, a nonconcentric roll, roll support looseness, drive train problems, or a worn felt may be diagnosed.

Antifriction bearings

A real-time analyzer is very effective at identifying defects in antifriction bearings. If the geometry and speed of a bearing are known, distinct frequencies can be calculated that will be emitted from the bearing for each part of the bearing that is defective. The geometry parameters that need to be known are the number of rollers, the diameter of the rollers, the pitch diameter, and the contact angle. From dynamics, the following equations can be derived for calculating the frequencies that will result from bearing defects.

$$C = (\text{rpm}/2)[1 - (d/D)\cos\Phi]$$

$$R = (D/2d)\text{rpm}\,[1 - (d/D)\cos\Phi]$$

$$O = (N/2)\text{rpm}\,[1 - (d/D)\cos\Phi]$$

$$I = (N/2)\text{rpm}\,[1 + (d/D)\cos\Phi]$$

where

C = cage frequency, cycles/min
R = roller frequency, cycles/min
O = outer race frequency, cycles/min
I = inner race frequency, cycles/min
d = ball or roller diameter, in.
D = pitch diameter, in.
N = number of balls or rollers
O = contact angle.

The results of these equations can be visually understood by taking a bearing and placing a mark on the outer race, the cage, and an inner race and then lining them all up. While holding the outer race stationary, rotate the inner race one complete revolution. The cage will have turned only about 40% of a revolution. The exact amount can be calculated from one of the previous equations. The cage speed is equal to this percentage of revolution times the speed of the inner race. The outer race frequency is equal to the cage speed times the number of rollers. The inner race frequency is equal to one minus the cage speed times the number of rollers.

If a defect was present in the outer race of the bearing, there would be an impact each time a roller passed over it. Therefore, the outer race defect frequency would be the number of rollers multiplied by the cage speed.

As an example, assume that the bearing has 20 rollers and that the cage rotates 40% of a revolution per revolution of the inner race. This would mean that $20 \times 0.4 = 8$, or eight rollers would pass over a defect in the outer race per revolution of the inner race.

I find frequency determination to be a better guide in determining bearing problems than amplitude. Amplitude is important, within reason, for a particular machine only after its history is developed. By the time a change in condition causes a measurable change in overall vibration, the bearing could be close to failure. Amplitude is dependent on support stiffness, load, running speed, and transmissibility of the signal. The same amount of damage to two identical bearings in different applications could result in large amplitude differences.

Signals from a defective bearing that is emitting a stable amplitude can give a sense of security for a while, but fast changes in amplitude can cause greater concern.

When using amplitude as a criterion, I prefer to use velocity readings. Velocity is a relatively uniform measurement across its frequency scale.

Amplitude and trending of amplitude can be very important in observing changes in equipment such as turbine-generators, fans, pumps and gearboxes.

Table I lists the relationship between the various amplitude descriptions.

Inner race problems

If an inner-race defect frequency appears first, I look at the situation more closely. I determine if there is a cracked inner race by looking at the time-domain signal. If a strong once-per-revolution peak is present in the time domain, then a crack may be present. These once-per-revolution peaks may have spikes between them that when calculated refer to the inner race defect frequency. I also check if the equipment is out of balance, which can lead to inner-race failures.

Corrosion

If the defect frequency harmonics seem to form a bell-shaped curve, past experience has revealed that corrosion may be present in the bearing at roller spacing.

Locked-up bearing

When a bearing locks up, it slides instead of rolls. Even though you would think it would be one of the easiest problems to detect, a locked-up bearing is hard to diagnose. It may produce a high base level of random noise with few distinct peaks. This situation may also produce a large amount of vibration at a once-per-revolution frequency. I have watched bearings as they have switched back and forth from sliding to rolling. The bearing defect frequencies will appear and then disappear with random noise becoming alternately present. If a bearing is loose on its shaft or journal, it will look much the same, but it might display more harmonics of running speed.

Priority of critical equipment

Developing a list of critical equipment to be surveyed should be done with the people that are responsible for each maintenance area of the mill. Try to keep these people involved because they can determine your success. When you find a problem, tell them immediately. When they call you to check a problem, react quickly. In making up a priority list, you should consider:

- The equipment without spares that can shut down or slow production
- The equipment with spares that can shut down or slow production
- Secondary equipment that is an inconvenience to production if shut down.

Let the people in each area know that you are going to need their support to help collect information on equipment, to notify you when a correction is made to a problem you have diagnosed, and to let you examine the replaced equipment.

Paper machine surveys

The first place to start surveys is on the paper machines. Their downtime is the most costly. Also, their analysis is probably easier than other equipment in the mill. In most cases, all you have is a roll with a bearing on each end. In addition, a large number of possible problems can be surveyed in a relatively short period of time.

One way of breaking up the surveys is as follows:

I. Amplitude conversion factors (sine wave only)

Description	*Multiply by*	*To obtain*
Average	1.57	Peak
	3.14	Peak to peak
	1.11	RMS
Peak	0.637	Average
	2	Peak to peak
	0.707	RMS
Peak to peak	0.318	Average
	0.5	Peak
	0.354	RMS
RMS	0.901	Average
	1.414	Peak
	2.828	Peak to peak

- Fourdrinier section
- Press section
- Dryer bearings
- Dryer felt rolls
- Dry end (breaker stack, size press, calender stack, and reel)
- Pinions
- Gearboxes
- Drive motors.

Usually these individual surveys can be performed in 1/2 hour to 3 hours. To perform the analysis of a survey can take from 10 minutes to 4 hours depending on the complexity of the survey.

Monitoring intervals depend on how rapid failures in these situations can develop. Experience is a vital guide. Survey frequencies can range from 2 weeks to 6 months. Once a problem is detected, it should be monitored more frequently.

There are three common positions for placing the vibration probes: vertical, horizontal, and axial. On a paper machine, I have had best results using axial readings. A clearer signal seems to be produced with less random noise. Therefore, readings should at least be taken in the axial direction.

If possible, surveys should be performed on both the front and back side of each roll. Most of the time, back-side bearing problems can be detected from the front side, especially dryer bearings and press-roll bearings. However, it is necessary to check felt rolls and smaller wet-end rolls from both sides.

On some older paper machines, you cannot get to the back-side dryer bearings with a portable probe due to open gears. In many cases, if you have a bad back-side bearing, it can be picked up on the front side with an axial reading. This seems to depend on the transmissibility of that particular machine and sometimes on which part of the machine is being analyzed. On some machines, if a bad back-side bearing is present, it can be detected several dryers down on the front side. If the signal transmits well from the back side to the front side, then you can take all front-side axial readings to determine if you have any problems. If the front-side and back-side bearings are different, then different defect frequencies will be emitted to determine which bearing is bad. If, however, both sides have the same bearing, then a front-side vertical reading can be taken in addition to the front-side axial reading. If the defect frequency goes away, then the problem is probably on the back side. If the defect frequency stays, then the problem may be on the front side. This is a quick check that will produce a likely prediction and not 100% accurate results. You can mount permanent probes on the back-side bearings, but this can be a very expensive and maintenance-intensive operation. A more effective method may be to install probes after a problem is detected from the front side or routinely move them during outages.

There are various companies promoting continuous monitoring of paper machine bearings. Some feel that this extra insurance is necessary. Others feel that it is too expensive just to detect and monitor bearing problems. Paper machine bearings usually fail slowly, and failure can be detected well in advance with periodic surveys.

In the beginning of a vibration analysis program, you might have to spend more time collecting and organizing detailed information about the equipment to be surveyed than collecting actual vibration data. By doing this in the beginning, the program is easier to carry out.

One aid is to develop computer-aided design drawings for all surveys. For paper machine surveys, they assemble the rolls into a logical order and numbering system.

To assist with the analysis of paper machine surveys, you may want to develop computerized spreadsheets with all the necessary information needed for analysis. Included on this sheet would be the following information:

- Machine speed (entered)
- Roll numbers
- Roll names
- Roll diameters
- Bearing manufacturers and sizes
- Bearing defect frequency multipliers
- Number of teeth on gears
- Roll speeds (calculated)
- Actual bearing defect frequencies (calculated)
- Gear-mesh frequencies (calculated).

A frequency spectrum derived from a single time waveform sample is called an instantaneous spectrum. To increase the accuracy of the reading, several samples should be taken and averaged. In most cases, four to eight averages are significant. The addition of more averages will require increased sampling time for limited accuracy improvement. The frequency scale should be set equal to at least 4-5 times outer race frequency, 3-4 times inner race defect frequency, or one time the gear-mesh frequency, depending on the situation.

Paper machine surveys can be performed by one or two people depending on the survey, safety, and ease of reaching bearings.

You should try to perform only very limited analysis in the field and spend more time looking at the rolls and getting the survey performed correctly and quickly. Standing next to a hot paper machine is not a suitable environment to perform proper analysis. It is better to perform the survey quickly and correctly and get back to the office so you can analyze the results.

Each vibration spectrum should be reviewed individually. In most cases, this can be performed very quickly. Since paper machine bearings are so repetitive, they can be analyzed almost as fast as you can push a key on the computer.

I have not found trending of amplitudes on a paper machine to be effective at all.

A report should be written periodically outlining the bearings that need to be replaced, their roll number, roll name, and a short description of the problem that exists.

Auxiliary equipment surveys

Auxiliary equipment is more challenging to analyze than paper machine bearings. As with the paper machine, full Fourier frequency transfer vibration-spectrum analysis can be performed at each point for auxiliary equipment. A mill will probably have 3000-10,000 points.

In addition to taking vibration readings, some other functions may need to be taken such as temperature readings, feeling the equipment, listening to it, and performing a visual inspection. Temperature readings can be taken with an infrared temperature sensor at each bearing location. The equipment can be listened to with a metal rod or an ultrasonic probe. Any problems that are detected should be duly noted, such as leaking pipelines, loose support feet, damaged guards, and safety hazards.

To perform the analysis on the auxiliary equipment efficiently and correctly, a considerable amount of time is required finding detailed information about each piece of equipment and organizing it. To be efficient and effective, you will need to have available the following type of information:

- Equipment number
- Equipment name
- Manufacturer
- Size or model
- Bearing positions, sizes, manufacturers, and defect multiplier frequencies
- Gear positions and number of teeth on each
- Number of vane or blades.

History collection

One of the best ways to improve the accuracy of a vibration analysis program is to develop good history files on your equipment. It helps for future analysis. You can never remember as much as you think you will. In addition, it may be beneficial to others who may be doing the analysis later on. Keep the following documentation and information:

- Information data sheets describing equipment
- Instrument set-ups and any necessary maps
- Dates of when equipment was monitored
- Printouts of vibration spectrum when problems are found. This should be continued until the problem is corrected and then filed for further reference. Include

photographs of any problems that were found and a short writeup of these problems.

In reviewing a vibration problem after repairs you need to ask yourself:

- Did these repairs eliminate a problem?
- Was this the correct problem to be worked on?
- How severe was the damage to the equipment?

Most importantly, you need to make people in the mill aware of your findings.

Critical points of a program

Vibration analysis programs at some mills have been ineffective, stalled, or eliminated for various reasons. For a program to be effective, it must have the support of both maintenance and production management.

In the beginning of any new program, there will be a learning period where mistakes may or may not occur. If management dwells on a mistake instead of backing up the program, the program will not develop.

Very few mills have had their programs fail due to poor equipment. Most fail because the right people are not involved. Some mills prefer to use millwrights due to their knowledge of the equipment. Other mills prefer to use salaried personnel who have the necessary analytical and computer skills for the analysis. It is necessary to find individuals who will obtain readings and perform analysis with speed and thoroughness. The individuals need to be good troubleshooters, open minded, and innovative. It is hard to find individuals who possess this combination of skills and who are also willing to perform sometimes hot, nasty, and repetitive work.

I believe that the individuals who collect the vibration readings in the field should also be involved with the analysis. Just collecting the data can be boring. By being a part of the analysis, you become more aware of the process. Therefore, the individual notices more detailed information in the field that can be beneficial to solving a problem. He or she also has a more self-satisfying role.

Vibration analysis is but one form of predictive and preventive maintenance. It will be more successful if it is performed in conjunction with such programs as lubrication, reliability, and downtime studies.

Do not limit yourself to depending just on the vibration signal. Other aids can help with the analysis: listening to bearings with a screwdriver or rod, listening to tape recordings of the vibration signal, taking oil samples, taking temperatures, feeling the machinery, and performing visual inspections.☐

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