INTRODUCTION TO VIBRATION TECHNOLOGY

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BACKGROUND

Machines of some kind are used in nearly every aspect of our daily lives; from the vacuum cleaner and washing machine we use at home, to the industrial machinery used to manufacture nearly every product we use on a daily basis. When a machine fails or breaks down, the consequences can range from annoyance to financial disaster, or personal injury and possible lose of life. For this reason, the early detection, identification and correction of machinery problems is paramount to anyone involved in the maintenance of industrial machinery to insure continued, safe and productive operation. This paper introduces you to the use of machinery vibration and the technological advances that have been developed over the years , making it possible to not only detect when a machine is developing a problem, but to identify the specific nature of the problem for scheduled correction.

VIBRATION AS AN INDICATOR OF MACHINERY CONDITION

How many times have you touched a machine to see if it was "running right"? With experience, you have developed a "feel" for what is normal and what is abnormal in terms of machinery vibration. Even the most inexperienced driver knows that something is wrong when the steering wheel vibrates or the engine shakes. In other words, it's natural to associate the condition of a machine with its level of vibration.

Of course, it's natural for machines to vibrate. Even machines in the best of operating condition will have some vibration because of small, minor defects. Therefore, each machine will have a level of vibration that may be regarded as normal or inherent. However, when machinery vibration increases or becomes excessive, some mechanical trouble is usually the reason. Vibration does not increase or become excessive for no reason at all. Something causes it - unbalance, misalignment, worn gears or bearings, looseness, etc.

Since not everyone has the long-term experience needed to judge a machine's condition based on how it feels, various instruments have been developed over the years to measure the actual level or amount of vibration. In addition, human perception of touch and feel is somewhat limited, and there are many common problems such as the early stages of bearing and gear failure that are generally out of the range of human perception. Thus, modern instrumentation for measuring vibration on rotating and reciprocating machinery not only minimizes the need for extensive experience, but makes it possible to detect developing problems that are outside the range of human senses of touch and hearing. Further,
human perception differs from individual to individual. What one person may consider as bad, another may consider as normal. Attempting to trend changes in machinery condition using human perception is nearly impossible, since it is nearly impossible to put a documented number on "how it feels".

To overcome this problem, instrumentation has been developed to actually measure a machine's vibration level and assign it a numerical value. This tool not only overcomes the limitations of inexperience, but it addresses the limitations of human perception as well.

WHAT IS VIBRATION?

Vibration can be defined as simply the cyclic or oscillating motion of a machine or machine component from its position of rest.

WHAT CAUSES VIBRATION?

Forces generated within the machine cause vibration. These forces may:

1. Change in direction with time, such as the force generated by a rotating unbalance.
2. Change in amplitude or intensity with time, such as the unbalanced magnetic forces generated in an induction motor due to unequal air gap between the motor armature and stator (field).
3. Result in friction between rotating and stationary machine components in much the same way that friction from a rosined bow causes a violin string to vibrate.
4. Cause impacts, such as gear tooth contacts or the impacts generated by the rolling elements of a bearing passing over flaws in the bearing raceways.
5. Cause randomly generated forces such as flow turbulence in fluid-handling devices such as fans, blowers and pumps; or combustion turbulence in gas turbines or boilers.

Some of the most common machinery problems that cause vibration include:

1. Misalignment of couplings, bearings and gears
2. Unbalance of rotating components
3. Looseness
4. Deterioration of rolling-element bearings
5. Gear wear
6. Rubbing
7. Aerodynamic/hydraulic problems in fans, blowers and pumps
8. Electrical problems (unbalance magnetic forces) in motors
9. Resonance
10. Eccentricity of rotating components such as "V" belt pulleys or gears

VIBRATION AND MACHINE LIFE

Your first question may be: "Why worry about a machine's vibration?" Obviously, once a machine is started and brought into service, it will not run indefinitely. In time, the machine will fail due to the wear and ultimate failure of one or more of its critical components. And, the most common component failure leading to total machine failure is that of the machine bearings, since it is through the bearings that all machine forces are transmitted. Of course, the next question is: "How long will be bearings last?" Although an exact answer to this question is impossible, the manufacturers of rolling element bearings attempt to estimate bearing life using the following calculation:

$$L_{10} \text{ LIFE (HOURS)} = (16{,}666/\text{RPM}) \text{ X } (\text{RATE/LOAD})^3$$

where: RPM = Machine rotating speed in Revolutions Per Minute

RATE = The rated load capacity of the bearing (lbs.)

LOAD = The actual load on the bearing. This includes not only the static load due to the weight of the rotor, but the dynamic load due to forces of unbalance, misalignment, etc., FORCES THAT CAUSE VIBRATION.

According to this calculation to estimate bearing life, doubling the rotating speed from, say 1800 RPM to 3600 RPM, would cut bearing life in half. However, by cutting the load on the bearing by one-half would increase its service life by eight times (2-cubed or 2 x 2 x 2 = 8). Of course, this estimate of bearing life does not take into consideration other factors such as inadequate lubrication, lubricant contamination or damage from improper storage or installation techniques.

From the above calculation, it can be seen that bearing load, including dynamic load from vibratory sources such as unbalance and misalignment, has a significant effect on bearing life and, ultimately, machine life. Further, the amount of vibration exhibited by a machine is directly proportional to the amount of force generated. In other words, if the unbalance force is doubled, the resultant vibration amplitude will be doubled also. Or, if the unbalance force is cut in half, the unbalance-generated vibration will be cut in half also. Therefore, the answer to the question: "Why worry about a machine's vibration?" is simple:

1. Increased dynamic forces (loads) reduce machine life.
2. Amplitudes of machinery vibration are directly proportional to the amount of dynamic forces (loads) generated. If you double the force, you double the vibration.
3. Logically then, the lower the amount of generated dynamic forces, the lower the levels of machinery vibration and the longer the machine will perform before failure.

It's really that simple. Low levels of vibration indicate low vibratory forces , resulting in improved machine life.

Of course, there are other reasons to strive for low levels of machinery vibration besides increasing the time between failures. In the case of precision machine tools, maintaining low levels of vibration is necessary in order to manufacture quality products from a dimensional tolerance and surface finish quality standpoint. In residences, office buildings and hospitals, low levels of vibration of heating, ventilation, air conditioning and other machinery is necessary to avoid human annoyance.

With few exceptions, when the condition of a machine deteriorates, one of two (and possibly both) things will generally happen:

1. The dynamic forces generated by the machine will increase in intensity, causing an increase in machine vibration.

   Wear, corrosion or a build-up of deposits on the rotor may increase unbalance forces. Settling of the foundation may increase misalignment forces or cause distortion, piping strains, etc.

2. The physical integrity (stiffness) of the machine will be reduced, causing an increase in machine vibration.

   Loosening or stretching of mounting bolts, a broken weld, a crack in the foundation, deterioration of the grouting, increased bearing clearance through wear or a rotor loose on its shaft will result in reduced stiffness to control even normal dynamic forces.

Thus, it should be obvious that an increase in machinery vibration is a positive indicator of developing problems. In addition, each mechanical or operational problem generates vibration in its own unique way. As a result, it is also possible to identify the specific nature of the problem by simply measuring and noting its vibration characteristics. The techniques of identifying specific defects and problems is presented in the section on VIBRATION ANALYSIS.

A COMPARISON OF MAINTENANCE PHILOSOPHIES

In general, there are three ways to maintain machinery:

1. Breakdown maintenance
2. Scheduled or "preventive" maintenance
3. Predictive maintenance

Breakdown Maintenance

Breakdown maintenance is essentially no maintenance at all. The machine is simply allowed to run until complete failure, inefficiency or product spoilage forces a shutdown.

Although many machines are maintained this way, breakdown maintenance has several disadvantages. First, failures can be most untimely and, there is little one can do beforehand to anticipate the tools, personnel and replacement parts that will be needed to return the machine to service. Secondly, machines allowed to run to failure generally require more extensive repair than would have been necessary if the problem had been detected and corrected early. Some failures can be catastrophic, requiring total replacement of the machine. It is estimated that, on the average, it costs approximately three times more to repair or replace a machine that has been allowed to run to total failure compared to the cost to repair a machine before failure. Catastrophic machine failure can also pose a safety problem for plant personnel. And, the added cost of lost production while the machine is out of service can be staggering.

Scheduled or Preventive Maintenance

Compared to breakdown maintenance, a program of periodic disassembly, inspection and replacement of worn parts has the distinct advantage of lessening the frequency of breakdown repairs and also permits scheduled shutdown. Under this program, each critical machine is shut down after a specified period of operation and partially or completely dismantled for a thorough inspection and replacement of worn parts, if any.

This approach to machinery maintenance, too, has disadvantages. First, to periodically dismantle every critical piece of equipment in the plant can be expensive and time consuming. Second, the interval between periodic inspections is difficult to predict. If the program is so successful that no machinery failures occur, it may be that the interval is too short and money and production is being wasted. If the interval is too long, costly failures may still occur.

Predictive Maintenance

Predictive maintenance involves the trending and analysis of machinery performance parameters to detect and identify developing problems before failure and extensive damage can occur. On-line detection and diagnosis of problems is obviously the most desirable way to maintain machinery. If problems can be detected early, when defects are minor and do not affect performance, and if the nature of the problem can be identified while the machine runs:

1. Shutdown for repairs can be scheduled for a convenient time.
2. A work schedule, together with the requirements for personnel, tools and replacement parts can be prepared before the shutdown.
3. Extensive damage to the machine resulting from forced failure can be avoided.
4. Repair time can be kept to a minimum, resulting in reduced machinery downtime.
5. Costly trial-and-error approaches to solve a problem can be avoided since analysis identifies the nature of the problem.
6. Machines in good operating condition can continue to run as long as no problems develop. Time and money are not wasted dismantling machines that are already operating properly.

VIBRATION AS A PREDICTIVE MAINTENANCE TOOL

There are many machinery parameters that can be measured and trended to detect the onset of problems. Some of these include:

1. Machinery vibration
2. Lube oil analysis including wear particle analysis
3. Ultrasonic (thickness) testing
4. Motor current analysis
5. Infrared thermography
6. Bearing temperature

In addition, machinery performance characteristics such as flow rates and pressures can also be monitored to detect problems. In the case of machine tools, the inability to produce a quality product in terms of surface finish or dimensional tolerances is usually an indication of problems. All of these techniques have value and merit. However, the one characteristic that is common to practically all machines is VIBRATION.

THE VIBRATION PREDICTIVE MAINTENANCE PROGRAM

A vibration predictive maintenance program consists of three logical steps:

DETECTION

ANALYSIS

CORRECTION

Detection

The first step of the program, detection, simply involves measuring and trending vibration levels at marked locations on each machine included in the program on a regularly scheduled basis. Typically, machines are checked on a monthly basis. However, more critical machines may be checked more frequently or, perhaps, continually with permanently installed on-line vibration monitoring systems. The objective is to reveal significant increases in a machine's vibration level to warn of developing problems.
A simple, hand-held vibration meter can be used to take a measurement of a machine's vibration level. The instrument includes a transducer that is held or attached to the bearing cap of the machine. The transducer converts the machine vibration into an equivalent electrical signal that is read on the meter as a vibration level. It is very important to know where and how to take vibration readings, and this is covered elsewhere in this paper.

Regular vibration readings taken with these "manual monitoring" instruments can be logged on a data sheet. This sheet includes a drawing of the machine to help the vibration technician identify measurement locations and positions. The form also includes provisions for recording the data in both tabular form as well as graphic trends to provide a clear history of the machine's condition. Any noted increase in the level of vibration is a positive warning of developing problems.

For programs that include only a small number of machines and measurement points, a manually operated instrument and data recording system, such as that described above, may be quite adequate. However, for programs that may include literally hundreds or, perhaps, thousands of machines and measurement points, a computerized data collection system is generally needed to not only minimize data collection time, but to minimize data evaluation as well. The typical system consists of a predictive maintenance software program installed in the computer and a compatible vibration instrument for collecting data in the field. Most systems not only provide for collecting and trending overall levels of machinery vibration, but also the detailed analysis data necessary to identify specific machinery faults.

The first step is to set up the program in the computer software that will include:

1. Listing all machines to be included in the program.
2. Identifying the bearing locations where readings will be taken on each machine.
3. Identifying the directions (horizontal, vertical and axial) where readings will be taken on each machine.
4. Identify the vibration parameters that will be measured at each location. Parameters other than vibration such as bearing temperature, speed (RPM), amps, pressures, flow rates, etc., may be incorporated as well.
5. Establish alarm or warning levels for each measurement.
6. Establish details for "spectral" (FFT) data needed for vibration analysis.
7. Organize machines into workable groups or "routes".
8. Establish a schedule for data collection for each group of machines.

At first glance, this may seem like a tedious and time consuming process. However, most vibration predictive maintenance software programs on the market today are very "user friendly" with numerous features that greatly simplify the process of setting up the program. Typically, a program can be set up for as many as 100 motor-pump systems in as little as an hour. Establishing measurement locations, alarm levels and analysis parameters requires additional training and/or experience.

Once the program has been set up in the computer software, the next step is to collect data. Based on the established schedule, a group of machines is selected and "loaded" into the vibration data collector instrument from the computer program. With the instrument loaded, the operator proceeds to the assigned area and turns the instrument on. The display on the instrument screen will direct the operator to the specific machine, measurement location and transducer direction for the measurement. Once the transducer is in place, the operator simply pushes the "store" button on the instrument to collect the data. Once the reading has been taken, the operator pushes a button to reveal the next required measurement. This process is repeated until all measurements on the route have been collected.

After the data has been collected, the operator returns to the computer and "down-loads" the data to the predictive maintenance software, following a few simple instructions. Once the collected data has been down-loaded, numerous reports can be generated to reveal those machines that have experienced a significant increase in vibration or have exceeded a preset alarm level, indicating developing problems.

A report is generated that identifies the specific machines, measurement points, vibration levels, alarm levels and percentage change from the last reading for those machines with developing problems.

Another useful report is the graphic trend. This allows the operator to see how the vibration reading has progressed over a period of time, to determine whether an increase in vibration has been gradual or sudden. Sudden increases in vibration are generally regarded as potentially more serious than those that have steadily increased over a period of weeks or months.

Alarms and trends are only a few of the many reports that can be generated by modern-day vibration predictive maintenance software programs. The automated data collectors and computerized data handling systems basically serve the same purpose as the simple hand-held vibration meter and data sheet. However, the automated systems allow the computer to do what it does best, and that is to "crunch" the numbers in a highly efficient and rapid manner. With a data collector, one technician can take vibration readings on many machines throughout a plant in a much shorter period of time.

Although most general machinery can be protected with periodic checks of vibration, some machines may not be well suited to "manual monitoring" techniques. High performance machinery such as steam and gas turbines, high-speed centrifugal compressors and pumps can develop problems very quickly, with little or no preliminary warning. Machines such as these may require continuous, on-line monitoring.

Analysis

Once machinery problems have been detected by manual or on- line monitoring, the obvious next step is to identify the specific problem(s) for scheduled correction. This is the purpose of vibration analysis - to pinpoint specific machinery problems by revealing their unique vibration characteristics.

In most cases, the same data collector instrument and software used for routine vibration surveillance and trending can be used to obtain the detailed vibration characteristics needed to pinpoint the specific problem. A systematic vibration analysis can then be carried out to identify the more common machinery problems, including:

Unbalance
Misalignment
Looseness
Defective Bearings
Resonance
Eccentricity
Worn Gears
Motor Electrical Problems
Drive Belt Problems
Distortion (Soft-Foot & Piping Strain)
Drive Belt Problems

Correction

Once problems have been detected and identified, required corrections can be scheduled for a convenient time. Of course, in the meantime, any special requirements for repair personnel (including outside repair facilities), replacement parts and tools can be arranged in advance to insure that machine downtime is kept to an absolute minimum.

If the vibration problem is diagnosed as unbalance, in many cases the same instrument used to detect and analyze the problem can be used to perform in-place balancing.

CHARACTERISTICS OF VIBRATION

Vibration is simply defined as "the cyclic or oscillating motion of a machine or machine component from its position of rest or its 'neutral' position."

Whenever vibration occurs, there are actually four (4) forces involved that determine the characteristics of the vibration. These forces are:

1. The exciting force, such as unbalance or misalignment.
2. The mass of the vibrating system, denoted by the symbol (M).
3. The stiffness of the vibrating system, denoted by the symbol (K).
4. The damping characteristics of the vibrating system, denoted by the symbol (C).

The exciting force is trying to cause vibration, whereas the stiffness, mass and damping forces are trying to oppose the exciting force and control or minimize the vibration.

Perhaps the simplest and easiest way to demonstrate and explain vibration and its measurable characteristics is to follow the motion of a weight suspended by a spring. This is a valid analogy since all machines and their components have weight (mass), spring-like properties (stiffness) and damping.

The motion of the mass from top to bottom range and back to the initial starting position in the vertical direction is referred to as one cycle, and it has all the characteristics needed to define the vibration. Continued motion of the spring-mass system will simply be repeating these measurable characteristics.

The characteristics needed to define the vibration include:

Frequency
Displacement
Velocity
Acceleration
Phase

Vibration Frequency

The amount of time required to complete one full cycle of the vibration is called the period of the vibration. If, for example, the machine completes one full cycle of vibration in 1/60th of a second, the period of vibration is said to be 1/60th of a second.

Although the period of the vibration is a simple and meaningful characteristic, a characteristic of equal simplicity but more meaningful is the vibration frequency.

Vibration frequency is simply a measure of the number of complete cycles that occur in a specified period of time such as "cycles-per-second" (CPS) or "cycles-per-minute" (CPM). Frequency is related to the period of vibration by this simple formula:

$$\text{Frequency} = 1/\text{Period}$$

In other words, the frequency of a vibration is simply the "inverse" of the period of the vibration. Thus, if the period or time required to complete once cycle is 1/60th of a second, then the frequency of the vibration would be 60 cycles-per-second or 60 CPS.

In the real world of vibration detection and analysis, it is not necessary to determine the frequency of vibration by observing the vibration time waveform, noting the period of the vibration and then taking and calculating the inverse of the period to find the frequency - although this can be done. Nearly all modern-day data collector instruments and vibration analyzers provide a direct readout of the vibration frequencies being generated by the machine.

Although vibration frequency may be expressed in cycles per second or CPS, the common practice is to use the term Hertz (abbreviated Hz) in lieu of CPS. This is in honor of Heinrich Rudolf Hertz, a 19th century German physicist who is credited with discovering electromagnetic radiation. Thus, a vibration with a frequency of 60 CPS would actually be expressed as 60 Hz.

Although vibration frequency can be measured and expressed in Hertz (Hz), for most machinery vibration work, vibration frequency is measured in cycles-per-minute, abbreviated CPM. Expressing vibration frequency in terms of CPM makes it much easier to relate this characteristic to the rotational speed of the machine that is normally expressed in revolutions- per-minute or RPM. Thus, if a machine operates at 3600 RPM, it is much more meaningful to know that a vibration occurs at 3600 CPM (1 x RPM) than 60 Hz.

Of course CPM and Hz can be easily converted to one another as follows:

Given a frequency expressed in Hz, you can convert it to CPM:

CPM = Hertz x 60 Seconds/Minute

Given a frequency expressed in CPM, you can convert it to Hz:

Hertz = CPM/60 Seconds/Minute

Significance of Vibration Frequency

There are literally hundreds of specific mechanical and operational problems that can cause a machine to exhibit excessive vibration. Obviously, when a vibration problem exists, a detailed analysis of the vibration should be performed to identify or pinpoint the specific cause. This is where knowing the frequency of vibration is most important. Vibration frequency is a very valuable analysis or diagnostic tool.

The forces that cause vibration are usually generated through the rotating motion of the machine's parts. Because these forces change in direction or amplitude according to the rotational speed (RPM) of the machine components, it follows that most vibration problems will have frequencies that are directly related to the rotational speeds.

To illustrate the importance of vibration frequency, assume that a machine, consisting of a fan operating at 2400 RPM and belt driven by a motor operating at 3600 RPM, is vibrating excessively at a measured frequency of 2400 CPM (1 x fan RPM), this clearly indicates that the fan is the source of the vibration and not the motor or belts. Knowing this simple fact has eliminated literally hundreds of other possible causes of vibration. Typical 1 x RPM vibration can be attributed to:

Unbalance

Eccentric Pulley

Misalignment

Bent shaft

Looseness

Distortion - soft feet or piping strain

Bad Belts - if belt RPM

Resonance

Reciprocating forces

Electrical problems

Determining that the frequency of excessive vibration is 2400 CPM (1 x fan RPM) has reduced the number of possible causes from literally hundreds to only ten (10) possible causes.

A little common sense can reduce this number of possible causes even further. First, since the vibration frequency is NOT related to the rotating speed (RPM) of the drive belts, belt problems can be eliminated as a possible cause. Secondly, since this is not a reciprocating machine such as reciprocating compressor or engine, the possibility of reciprocating forces can be eliminated from the remaining list. Finally, since the frequency is not related to the drive motor in any way, the possibility of electrical problems can be eliminated. Now, the number of possible causes of excessive vibration has been reduced to only seven (7) by simply knowing that the vibration frequency is 1 x RPM of the fan.

Vibration analysis is truly a process of elimination. Additional tests and measurements can be taken to further reduce the number of possible causes of a vibration problem. However, it should be obvious that knowing the frequency of vibration and how the frequency relates to the rotating speed of the machine components is truly the first step in the analysis process.

Of course, not all machinery problems will generate vibration at a frequency equal to the rotating speed (1 x RPM) of the machine. Some problems such as looseness, misalignment, resonance and reciprocating forces can often generate vibration at frequencies of 2x, 3x and sometimes higher multiples of RPM. Problems with gears usually result in vibration at frequencies related to the "gear mesh" frequency or the product of the number of teeth on the gear multiplied by the gear RPM. Aerodynamic and hydraulic problems with fans and pumps will normally show vibration frequencies that are the product of the machine RPM times the number of fan blades or impeller vanes. In addition, not all problems will result in vibration frequencies that are directly related to the rotating speed of the machine. The vibration frequencies generated due to flaws or defects in rolling-element bearings is a good example.

In summary, it is important to realize that different machinery problems cause different frequencies of vibration and that is the significance of knowing the frequency of vibration

Vibration Amplitude

As mentioned earlier, vibration frequency is a diagnostic tool, needed to help identify or pinpoint specific mechanical or operational problems. Whether or not a vibration frequency analysis is necessary, depends on how "rough" the machine is shaking. If the machine is operating smoothly, knowing the frequency or frequencies of vibration present is not important. The magnitude of vibration or how rough or smooth the machine vibration is, is expressed by its vibration amplitude. Vibration amplitude can be measured and expressed as:

- Displacement
- Velocity
- Acceleration

The following paragraphs describe each of these units of vibration amplitude, their significance and applications.

Vibration Displacement

The vibration displacement is simply the total distance traveled by the vibrating part from one extreme limit of travel to the other extreme limit of travel. This distance is also called the "peak-to-peak displacement".

Peak-to-peak vibration displacement is normally measured in units called mils, where one mil equals one-thousandth of an inch (1 mil = 0.001 inch). A measured vibration amplitude of 10 mils simply means that the machine is vibrating a total distance of 0.010 inches peak-to-peak.

In Metric units, the peak-to-peak vibration displacement is expressed in micrometers (sometimes called microns), where one micrometer equals one-thousandth of a millimeter (1 micrometer = 0.001 millimeter).

Electronic instruments for measuring vibration on industrial rotating machinery did not become readily available until the late 1940's and early 1950's, although the significance and importance of measuring vibration as an indicator of machinery condition had been well known for decades. Until the introduction of electronic instruments, instruments used to physically measure a machine's vibration were mechanical devices such as seismically-mounted dial indicators, light-beam vibrometers and mechanical linkage devices that magnified the relatively small amplitudes of machinery vibration to levels that could be visually observed. Obviously, with these mechanical devices, the only parameter of vibration that could be measured was the peak-to-peak displacement. As a result, the first guidelines and acceptance standards for machinery vibration were given in units of vibration displacement. A vibration severity chart based on displacement first appeared in an article by Mr. T. C. Rathbone entitled "Vibration Tolerances" in the November 1939 issue of Power Plant Engineering. While the chart was the first of its kind, it was limited in its consideration of frequency of vibration.

The fact that the severity of a vibration depends not only on displacement but frequency as well is understandable when one realizes that the vast majority of machinery failures caused by problems that generate vibration are FATIGUE problems. To illustrate, consider what happens when a piece of wire is repeatedly bent back and forth. This repeated bending eventually causes the wire to break due to fatigue in the area of the bend. In many respects, this is exactly the way a machine component fails - from the repeated cycles of flexing caused by excessive vibratory forces.

Considering the example of repeatedly bending a piece of wire, there are two ways to reduce the amount of time required to achieve fatigue failure. One is to increase the distance (displacement) that the wire is bent. The farther the wire is bent each time, the less time it will take to reach fatigue. The other is to increase the number of times per minute or second (frequency) the wire is bent. The more times per minute the wire is flexed, the less time it will take to reach fatigue failure. Thus, the severity of vibration is dependent on both vibration displacement and frequency.

The Problem With Displacement

Although measurements of vibration displacement have been used for many years to evaluate machinery condition, the fact that it is necessary to know the frequency as well, makes the use of displacement somewhat cumbersome when dealing with a vibration predictive maintenance program that may include virtually hundreds of machines and literally thousands of measurements.. In addition, it has already been shown that machinery vibration is not always simple or occurring at only one frequency. In many cases, machinery vibration will be complex, consisting of many frequencies. In such cases, it is nearly impossible to use vibration displacement to judge the "overall" condition of a machine. It must be remembered that each source of vibration contributes to the ultimate fatigue of machine components, and the "overall" condition of the machine can only be determined by an overall measurement of vibration that takes into account all frequencies of vibration. This is accomplished by measuring VIBRATION VELOCITY.

Vibration Velocity

It was pointed out earlier that the vast majority of machine failures caused by vibration problems are fatigue failures. And, the time required to achieve fatigue failure is determined by both how far an object is deflected (displacement) and the rate of deflection (frequency). Of course, displacement is simply a measure of the distance traveled and frequency is a measure of the number of times the "trip" is taken in a given period of time such as a minute or second. If it is known how far one must travel in a given period of time, it is a simple matter to calculate the speed or velocity required. Thus, a measure of vibration velocity is a direct measure of fatigue. In short:

Fatigue = Displacement x Frequency,

Velocity = Displacement x Frequency,

Thus,: Velocity = Fatigue.

Vibration velocity is a measurement of the speed of movement of a machine or machine component as it undergoes oscillating motion. Since the weight is moving, it must be moving at some speed determined by the displacement and frequency. However, the speed of the weight is constantly changing. At the upper and lower limits of travel, the velocity is zero (0), since the weight must come to a stop before it can go in the opposite direction. The velocity is the greatest or at its peak as the object passes through the neutral position. Velocity is definitely a characteristic of the vibration, but since it is constantly changing throughout the cycle, the highest or "peak" velocity is selected for measurement.

Vibration velocity is expressed in inches-per-second peak (in/sec-pk) for English units. In Metric units, vibration velocity is expressed in millimeters-per-second peak.

The fact that vibration velocity is a direct indicator of fatigue and vibration severity is clearly indicated by the General Machinery Vibration Severity Charts. The benefits and advantages of measuring vibration velocity instead of vibration displacement include:

1. Vibration velocity is a direct indicator of fatigue since it takes into account both displacement and frequency.
2. It is not necessary to know the frequency of vibration in order to evaluate the severity of vibration velocity since frequency is already a part of velocity.
3. A measurement of overall vibration velocity is a valid indicator of the overall condition of a machine whether the vibration is simple (one frequency) or complex (more than one frequency).

For the reasons listed above, vibration velocity has become the industry standard for evaluating machinery condition based on vibration.

As a word of caution, it is not possible to use the velocity measurement solely to establish absolute vibration tolerance levels on machines. In other words, there is no absolute vibration level dividing continuous operation and immediate failure. The objective of a predictive maintenance program is simply to detect problems so that they can be identified and corrected before failure. The objective is NOT to see how much vibration a machine can tolerate before failure.

Vibration Acceleration

The speed or velocity of a vibrating object is constantly changing. At the extreme limits of travel the velocity is zero (0) since the object must stop momentarily to change direction. Of course, each time the object comes to a stop at the limit of travel, it must "accelerate" to pick up speed as it travels towards the other extreme limit of travel. VIBRATION ACCELERATION is another important characteristic of vibration that can be used to express the amplitude or magnitude of vibration. Technically, acceleration is simply the rate of change of velocity.

Referring to the time waveform plot of the vibrating spring- mass system, the acceleration of the weight is maximum or at its peak value at the upper limit of travel where the velocity is zero (0). As the velocity of the weight increases, the rate of change of velocity or acceleration decreases. At the neutral position, the weight has reached its maximum or peak velocity and at this point, the acceleration is zero (0). After the weight passes through the neutral position, it must begin to slow down or "decelerate" as it approaches the lower limit of travel. At the lower limit of travel the rate of change of velocity (acceleration) is, again, at its peak value.

As with velocity, since the value of vibration acceleration is constantly changing, the highest or peak acceleration is selected for measurement.

Since vibration acceleration is technically the rate of change of vibration velocity (in/sec-peak or mm/sec-peak), it follows that the units of vibration acceleration could be expressed in in/sec/sec-peak or mm/sec/sec-peak. This can also be written as:

$$\text{in/sec/sec} = \text{in/sec}^2$$

or

$$\text{mm/sec/sec} = \text{mm/sec}^2$$

However, by international agreement, levels of machinery vibration acceleration are expressed in units of "G's", where one (1) "G" is the acceleration produced by the Earth's gravitational force at sea level. By international agreement, the values of 980.665 cm/sec/sec, 386.087 in/sec/sec and 32.1739 feet/sec/sec have been established as the standard acceleration values due to Earth's gravity at sea level. Thus, a measured vibration acceleration of 1-G peak would be approximately 386 in/sec/sec (980 cm/sec/sec).

It should be kept in mind that the Earth's gravitational force (G) has little to do with a machine's vibration amplitude. A machine with mechanical and/or operational problems will vibrate regardless of where it is located - on Earth or in gravity-free outer space. The accepted practice of expressing vibration acceleration amplitudes in G's is simply one of convenience and familiarity.

As with vibration amplitudes expressed in displacement and velocity, some guidelines are needed to evaluate vibration amplitudes measured in G's acceleration. It should be noted that judging or evaluating vibration acceleration (G) measurements is similar to evaluating vibration displacement measurements in that it is necessary to know the specific frequency of vibration.

When To Use Displacement, Velocity, And Acceleration

From the preceding discussions, it should be apparent that the magnitude or amplitude of machine vibration can be expressed in units of displacement, velocity, or acceleration. In addition, it was pointed out that the vast majority of machine failures were the result of fatigue, that vibration velocity was a direct measure of the fatigue aspect of vibration and that most machinery vibration acceptance standards were, in fact, based on vibration velocity measurements. The obvious question at this point should be: "Why measure vibration displacement or acceleration?" Actually, the answer is quite simple. Although the vast majority of machinery failures are due to fatigue, as it is directly related to vibration velocity, there are two other causes or "mechanisms" of machinery failure:- stress and force. These two parameters are directly related to vibration displacement and acceleration, respectively.

The fatigue failure of machine components from repeated cycles of flexing and the direct relationship between vibration velocity and fatigue have been explained. However, due to brittleness, many machine components may crack or break if simply bent or deflected (displaced) beyond a certain limit. High amplitudes of vibration displacement may cause mounting bolts to snap, welds to give way or concrete bases and foundations to crack. - not because of fatigue, but simply because they were deflected beyond their yield points.

Where high amplitudes of vibration displacement usually occur that result in stress failures is typically at very low vibration frequencies - generally below 600 CPM (10 Hz). Hence, whenever it is anticipated that vibration frequencies may be present at frequencies below 600 CPM (10 Hz), measurements of vibration displacement are recommended.

As a general rule, fatigue failures typically result from vibration frequencies between approximately 600 CPM (10 Hz) and 120,000 CPM (2000 Hz). Therefore, when vibration frequencies within this range are anticipated, measurements of vibration velocity are recommended.

The concept of relating stress to displacement and fatigue to velocity is fairly simple and straightforward. Perhaps the easiest way to demonstrate force as a cause of trouble is to simply consider striking an object with a hammer. The impact may not cause significant displacement or velocity; however, resultant damage can be considerable.

From our earliest science classes we were taught that force equals mass times acceleration (F = M x A). From this simple formula, it is apparent that vibration acceleration is directly proportional to vibratory force. And, since vibration acceleration increases proportional to the square of vibration frequency, very large vibratory forces can occur at high frequencies of vibration even though the displacement and velocity amplitudes may be quite small.

Excessive forces generally cause deformation of the surfaces of machine components such as gear teeth and rolling element bearings. High forces can also cause the lubricating film to break down, resulting in friction, heat generation and ultimate failure.

Because of the importance of vibratory forces at high frequencies, vibration acceleration measurements (G's) are recommended whenever vibration frequencies above 120,000 CPM (2000 Hz) are anticipated. Probably the most common source of such high frequencies are gear-mesh frequencies and harmonics or multiples of gear mesh frequencies on high-speed gear drives.

Phase

In addition to frequency (Hz or CPM) and amplitude (displacement, velocity, and acceleration), the third and final characteristic needed to describe a machine's vibration behavior is PHASE.

Phase, with regards to machinery vibration, is often defined as "the position of a vibrating part at a given instant with reference to a fixed point or another vibrating part". Another definition of phase is: "that part of a vibration cycle where one part or object has moved relative to another part".

The concept of "phase" is often the most confusing to newcomers to the field of vibration detection and analysis; however, from a practical standpoint, phase is simply a convenient means of determining the "relative motion" of two or parts of a machine or vibrating system. The units of phase are degrees, where one complete cycle of vibration equals 360 degrees.

To demonstrate phase, consider two weights vibrating at the same amplitude and frequency; while weight "A" is at the upper limit of travel ready to move downward and, at the same instant, weight "B" is at the lower limit of travel ready to move upward. Phase can be used to express this comparison. By plotting once cycle of motion of these two weights, it can be seen that the points of peak amplitude are separated by a half cycle or 180 degrees (one complete cycle = 360 degrees). Therefore, these two weights are vibrating 180 degrees "out of phase".

Significance Of Phase

Normally, phase measurements are not taken during routine periodic checks or the "detection" phase of a predictive maintenance program. However, when a developing problem is detected, comparative phase measurements can provide invaluable information as part of the analysis to aid in pinpointing the specific problem.

Unbalance
Bent shafts
Misalignment of couplings, bearings and pulleys
Looseness
Distortion from soft feet and piping strains
Resonance
Reciprocating forces
Eccentric pulleys and gears

Determining the "relative motion" of various machine components can help greatly to reduce this list of possible causes.

Phase Measurement Techniques

There are many ways to measure the phase of machinery vibration, depending on the type of vibration analysis instrumentation available. However, the two most common methods of phase measurement provided with most portable vibration analyzers and data collectors are:

1. The stroboscopic (strobe) light

2. Digital phase angle display (from reference input).

Not only will phase measurement provide an important tool for relative motion studies, it is an essential input for balancing.

ADDITIONAL APPLICATIONS FOR VIBRATION DETECTION & ANALYSIS

Although this paper emphasizes the use of vibration control for predictive maintenance, there are many additional applications that include:

Incoming Inspection: Many companies perform vibration and balance checks on newly purchased or rebuilt machines and machine components. Inspection of such items as gear boxes, motors, couplings, pump and fan rotors, etc., ensure that they meet quality standards.

One company recently reported setting up a test facility to check the quality of new replacement bearings. Another company tests new as well as rebuilt machine tool spindles to make sure they perform properly before installation.

These companies have learned through experience that detecting faulty components before they are installed is easier and considerably less costly than tracing the problem after installation and startup.

Machinery Acceptance Standards: Over the past three decades, many industries as well as manufacturing, engineering and standards organizations and government agencies have established vibration acceptance levels for newly installed machinery. Some of these standards include:

American Petroleum Institute (API)
International Standards Organization (ISO)
U.S. Government Services Administration (GSA)
U.S. Veterans Administration (VA)
National Electrical Manufacturers Association (NEMA)
National Gear Manufacturers Association (AGMA)
Hydraulics Institute (Pumps)

By including maximum acceptable levels of vibration in machinery purchase, repair and installation specifications, you can be assured that a piece of equipment will be in good operating condition and meet anticipated performance and reliability expectations.

Quality Control: Many manufacturers use vibration detection and analysis techniques in various ways to minimize waste and to insure the quality of their products. For example, a major manufacturer of automobile engines was experiencing high rejection rates on machined engine blocks due to poor cylinder bore finish. A vibration monitor (the same type used for predictive maintenance) was installed on the 16-spindle boring mill. Whenever a significant increase in vibration occurred, the vibration monitor shut down the boring mill and also identified the defective spindle for immediate correction. This technique not only improved the quality of cylinder bore finish, but significantly reduced downtime and product waste.

Detecting, pinpointing and correcting excessive vibration in machine tools improves product quality and also increases tool life. Balancing of grinding wheels in-place following replacement or truing saves time and assures continued productivity and product quality.

Of course, vibration detection and analysis techniques apply directly to the products being manufactured as well as the machinery used in their production. Vibration testing of assembled machines and components leads directly to improved product quality.

Dynamic balancing of rotating assemblies is an important element in the correction phase of a complete predictive maintenance program. However, the same procedures and instrumentation can be used in the production of new or rebuilt machinery. Without question, most reputable manufacturers of rotating and reciprocating machinery include dynamic balancing as a normal part of the manufacturing process.

Engineering: Vibration detection and analysis play important roles in the development and testing of new or prototype machines. Vibration measurements provide overall performance data. Analysis techniques reveal troubles that might be the result of improper installation and adjustment as well as improper design.

Field Service: In spite of the many engineering tests and quality control inspections, vibration problems do occur once a machine is delivered, installed and brought into service.

Such problems may include:

- Damage to the machine during transportation or installation
- Improper alignment of couplings or pulleys
- Weak or inadequate base or foundation
- Resonance of the machine or a machine component
- Distortion due to "soft foot" or piping strain
- Machine operating outside designed performance parameters
- Improper design of related components such as piping, duct work, etc.

Due to the multitude of problems that can result in vibratory forces, a complete vibration analysis of the complete installation is often the only way to clearly define the source of a problem and the corrective action required for its solution.

SUMMARY

Regardless of the application, - predictive maintenance, quality control, field service, etc. - vibration detection and analysis techniques do work. Making them work requires the proper vibration measurement and analysis equipment. Equally important, if not more so, is the vibration technician - an individual properly trained to use the equipment effectively.

Instruments provide the necessary information about a machine's vibration, but it is up to you to study, evaluate and interpret the data. It is up to you to pinpoint the problem and prescribe corrective action. To do this requires two important skills. The first is one that you already have: a basic knowledge and understanding of machines and how they work, the problems common to these machines, and how to correct them. The second skill is the ability to recognize and pinpoint mechanical and operational problems. Vibration measurement and analysis are key in developing this skill.

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