

A Brief Tutorial on Machine Vibration

by

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The purpose of this tutorial is to provide sufficient knowledge to understand machine vibration diagnosis. You may be tasked with solving a vibration problem, or you may be overseeing someone else and you need to understand the process. This tutorial discusses the symptoms, taking measurements, analyzing the data, additional testing, understanding the physics, and finally, fixing the problem. It provides practical information that has proven useful over several decades in correcting all types of machine vibration problems, with a few tenacious exceptions. There are usually several technical solutions to any vibration problem, and this tutorial will guide you through the choices.

The first step is to understand the problem from its outward symptoms. This means observation and measurements to quantify the symptoms, and then analysis to interpret the data. It is usually best to proceed from a position of knowledge while deflating opinions that are not supported by the data. The diagnosis is the shorter part of the journey, taking one person several hours to accomplish, but is the most important part because recommendations here will commit many persons and many hours to remedial work. We would like the correction to be successful on the first attempt.

Strategy

All vibration is not bad. Machines produce some oscillatory motion as part of their normal operation and these are nothing to be concerned about. I call these benign vibrations and here are some examples:

- 120-Hz motor hum
- blade passing frequency
- pure tones from motors, especially those driven by VFD's
- broadband turbulence from fluid-handling machines, like fans and pumps
- gearmesh frequencies

These benign vibrations are characteristic of regular operation of a machine doing what it is supposed to do. The amplitudes will vary from machine to machine and are a measure of the quality of manufacturing and load condition. The presence of these benign vibrations at "normal" levels provides a comfortable feeling that the machine is still alive. A change above normal levels not explained by a corresponding load change is reason for investigation, but not alarm. Serious vibration are:

- 1x-rpm amplitudes above the balance limits in Table 1.
- shock pulses
- large shaking motion
- abnormal noise

These serious vibrations will cause accelerated wear and premature failure. They should be acknowledged as damaging and addressed with some corrective action.

The first task for the vibration analyst is to obtain frequency selective amplitude data to identify the source of vibration. The frequency is the key information that establishes the possible causes and then the amplitude is used to judge the severity. This means having a vibration analyzer at one's disposal. More on this in the section "Instruments and Methods." This takes us to the first fork in the analysis flowchart, Figure 1. The

appropriate question to ask when armed with the frequency and amplitude data is whether the vibration is benign or serious. If it is benign, then we can safely ignore it. It may, however, cause concern for a sensitive occupant nearby by virtue of transmitting to that space and interfering with that process. An example is a rooftop fan that shakes a delicate optical microscope below. In this case the fan may be O.K. but we need to treat the path of vibration. The corrective action to take for benign vibrations that are not bothering anyone is to explain this to those concerned, and perhaps monitor this vibration for a time to verify that it is not trending upward in amplitude.

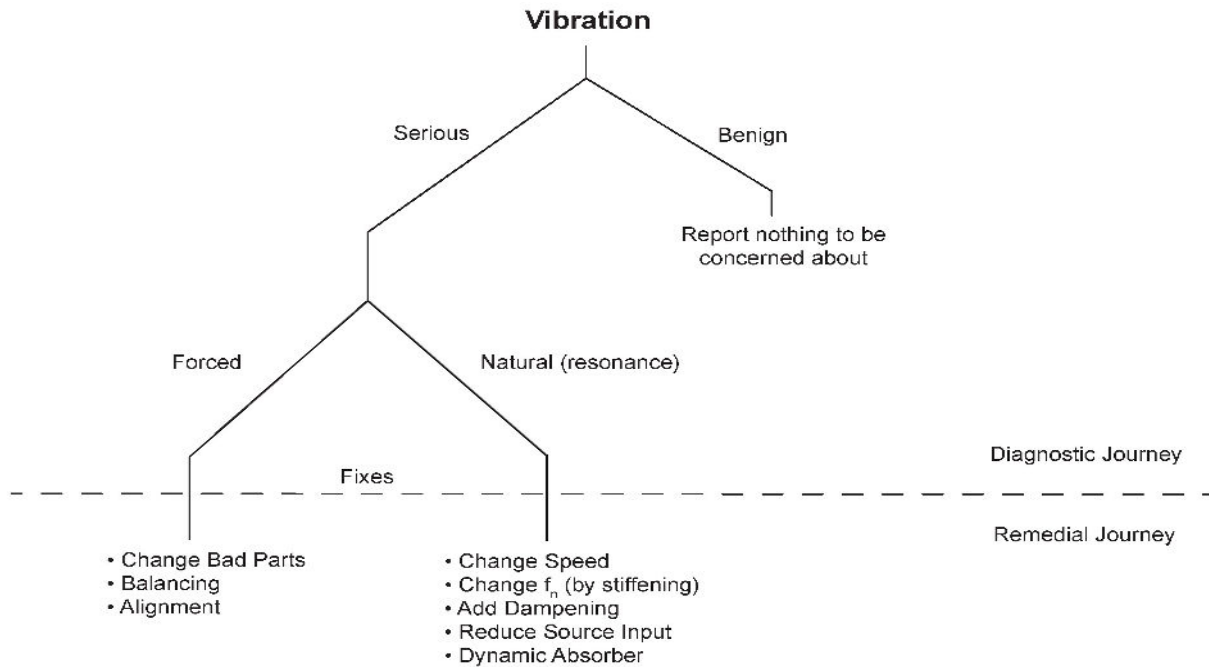


Figure 1. Vibration Flowchart

If the vibration is deemed to be serious, then this takes us to the second fork in the flowchart—forced versus natural vibration. This requires additional testing; usually stopping the machine to do resonance testing, a visual inspection, cleaning if necessary, and runout measurements with a dial indicator. The reason for determining early whether the vibration is forced or natural is because the fixes are completely different. Forced vibrations on machines are corrected by mass balancing, aligning, or changing the bad parts. Natural vibrations are a structural effect, where some structure behaves like a mechanical amplifier that is frequency sensitive. The symptoms of natural vibrations, or resonance, are:

1. The vibration is very bad, in other words, abnormally high amplitude.
2. The vibration is strongly directional.
3. The amplitude is not steady, but varies up and down.
4. Rumbles during runup or coastdown as harmonics pass through the natural frequency.

Once a resonance is suspected from the symptoms, then it needs to be verified with some additional tests. These resonance tests are:

1. Impact testing of the major components to find their natural frequencies.
2. Variable-speed shaker
3. Runup or coastdown
4. Operating deflection shapes

These tests require specialized equipment and methods to obtain valid results. For example, Tests 1 and 2 are done with the machine stopped using an instrumented hammer or a electrodynamic shaker with a power amplifier. Test 3 requires recording the data and Test 4 is done during normal operation taking amplitude, and perhaps phase, measurements along a grid pattern. The positive outcome of this is that during the testing a corrective fix usually becomes obvious. The five known fixes for resonance are:

1. Change speed
2. Change the natural frequency of the responding part with added mass or stiffness.
3. Add damping
4. Reduce the source vibration input.
5. Dynamic absorber

Table 1. Vibration Limits

Vibration Limits	Balance Condition Displacement, mils Peak to Peak at 1x rpm	Overall Velocity in/sec Peak 10 - 1,000 Hz	Overall Acceleration, g Peak 0 - 5,000 Hz
Electric Motors 1,000 - 2,000 rpm	2.0	0.2	0.5
> 2,000 rpm	1.0	0.2	1.0
Generators	2.0	0.2	0.5
Centrifugal Fans < 600 rpm	4.0	0.3	0.5
600 -1,000 rpm	3.0	0.3	1.0
1,000 – 2,000 rpm	2.0	0.3	1.5
> 2,000 rpm	1.0	0.3	2.0
Vaneaxial Fans	1.0	0.2	0.5
Blowers	1.0	0.3	0.5
Pumps	2.0	0.2	0.5
Centrifugal Compressors	1.0	0.2	3.0
Cooling Tower Gearboxes	3.0	0.4	2.0
Reciprocating Engines Gas or Diesel	5.0	1.0	10.0
Turbines	1.0	0.2	0.5
Gearboxes	1.0	0.4	2.0
Twin Screw Compressors	1.0	1.0	15.0

These fixes are very different from the balancing, alignment, or changing parts for forced vibrations, so it is important to identify this fork in the road before proceeding down the wrong path.

What is Acceptable

Table 1 is a general guide for acceptable vibration on many classes of common machines. This table was compiled from industry standards, some published specifications, from manufacturers' factory balance levels on new equipment, and from field experience. These limits apply for measurements at, or as close as safely possible to, the bearings. These guidelines are general in that they are economically achievable and vibration below these levels will allow the machine to survive a normal life in service. These levels may need to be reduced for product-quality purposes, or for stealthiness in military applications. The levels may need to be allowed to float above these levels for flexible-mounting conditions, such as springs or elevated platforms. Higher levels may also need to be allowed when higher-vibration sources are nearby. An example is a diesel engine driving a gearbox and a high-speed pump, all on the same common skid base. The gearbox and pump vibration may not meet their specified levels because of the thumping from the engine, but all three machines may be O.K. to operate as is.

Instruments and methods

A vibration measuring instrument separates the frequencies and quantifies the amplitude, Figure 2. It converts the physical motion into an electrical signal that can be further processed and displayed along a frequency axis. It provides us with the "big picture" of vibration by identifying the specific causes with the frequency and judging acceptability with the amplitude. There are three major categories of vibration instruments, each of which can use a velocity transducer or accelerometer as the sensor.

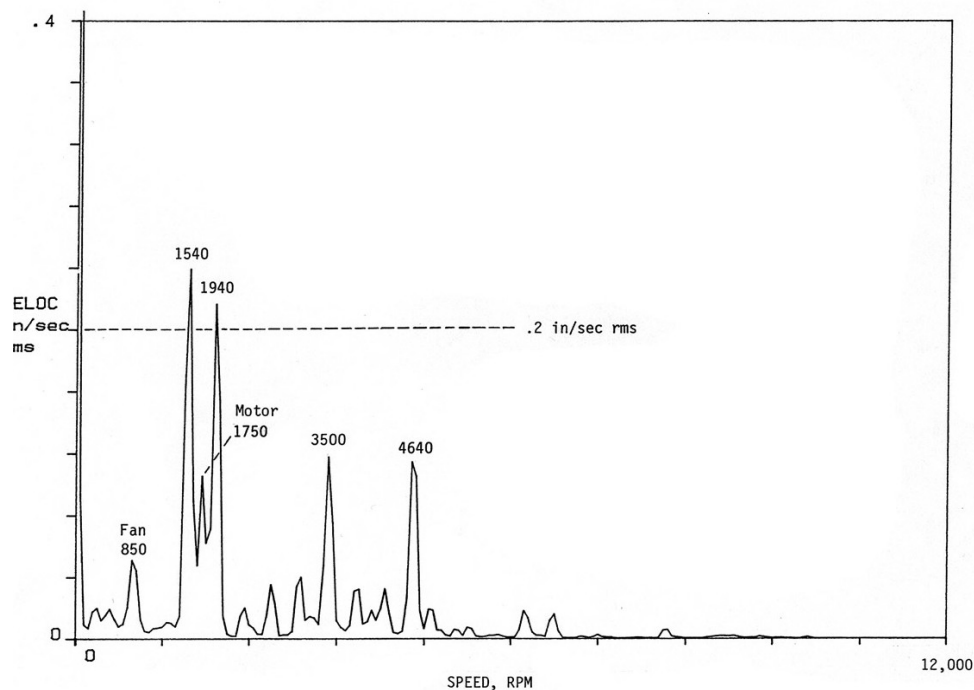


Figure 2. An FFT Spectrum

The simplest, and least expensive, is an overall meter. It provides no frequency information, only overall amplitudes, so it is useless for analysis. It is useful for trending or comparison measurements on similar machines, but for diagnosing problems on machines it is best left turned off.

The other two major vibration instruments are tuneable filters and FFT (Fast Fourier Transform) analyzers. Analyzer is a misnomer because analysis is a human function. An electronic “analyzer” does no analysis. It only measures and display electrical signals. The electrical signals from accelerometers and velocity transducers are very small AC voltages, typically millivolts. Hence, the tuneable filters and FFT instruments are nothing more than fancy AC voltmeters with a frequency display axis. Vibration instruments have been grossly oversold in the past two decades under the guise of computer intelligence. Any of these two major vibration measuring instruments, from any manufacturer, can be used effectively to diagnose machine vibrations. No specific instrument or manufacturer has a unique connection to a higher intelligence. However, some are an order of magnitude or two more complicated to use by design. The instrument in use is the least significant factor in diagnosis. The instrument operator and the methods employed are the most significant.

The fundamental method of using a vibration instrument is to conduct a survey of the entire machine system; driver, driven, and any intermediary machines such as gearboxes. The purpose of this survey is to map out the entire system at least once so as not to overlook anything before diving into details. Calmly, and objectively, gather the numbers in tabular form to be able to view it all in one image. Table 2 is a sample form.

Table 2. Vibration Survey Form

Equipment		Displacement Mils, peak-to-peak Filtered to 1xRPM	Overall Velocity In/sec, RMS 10-1,000 Hz	Overall Acceleration g/ peak 0 – 5,000 Hz
Motor ODE	Horizontal Vertical Axial			
DE	Horizontal Vertical Axial			
Pump DE	Horizontal Vertical Axial			
ODE	Horizontal Vertical Axial			

The first column measures the balance condition. The second column measures vibration severity in accordance with ANSI S2.41 in the low-frequency spectrum. The third column characterizes the shock pulses from the bearings. The survey technique is to concentrate on obtaining valid measurements while at the machine, and not focusing immediately on any specific peak. Hand-held, or magnet-mounted, data is acceptable if care is taken in hand holding in a steady manner, perpendicular to the surface, with a constant pressure, and with a magnet to verify that it does not rock. Quality of data acquisition is important in this initial survey, rather than quantity. Analysis will come later after the complete picture is assembled.

This initial survey allows us to determine quickly if the problem is in the motor or the pump, whether it is directional, the balance condition, the bearing condition, and some information about possible distortion from the velocity overall. The displacement and velocity numbers can be compared to national standards for acceptability, some of which are in Table 1. There are no standards for acceleration to determine bearing acceptability because the shock pulses must be tempered with size of bearing and speed of rotation, but the relative measurements allow us to quickly identify the worst and best bearings.

In addition to this tabulated data, listen to the bearings with a stethoscope and hand feel the vibration. Ten mils should feel like 10.0 mils. This protects us from “meterosis and digitosis,” diseases of the mind unique to vibration analysts. I, for one, do not trust any electronic instrument, but I will accept the numbers with caution.

Machines produce an abundance of vibration data coded in the vibration signal. Machine environments also produce plenty of contaminating signals that corrupt the real data, at no extra charge. It is the analyst's responsibility to recognize contaminating signals as invalid data and reject them. Be suspicious of anything at exactly 60 Hz and its harmonics. It is probably electrical noise invading the measurement system. Intermittent electrical connections produce signals similar to Figure 3. The time trace is not symmetrical about the zero amplitude line. Normal physical vibration swings both positive and negative and spends an equal amount of time above the zero axis line as below it. The frequency spectrum in Figure 3 is from an intermittent connection and has unusually high broadband energy.

Any time trace signal that has very sharp rise times is not real physical motion. Physical objects cannot jump from one position to another in microseconds. Sharp rise times are probably intermittent cable connections or electromagnetic noise from power semiconductor switches or radio transmissions nearby. The time display shows this better. The bane of vibration measurements is that we are dealing with extremely low-level AC signals that are easily contaminated in machine-room environments.

As an option, consider measuring phase also at 1x-rpm to visualize how the machine is shaking. Phase at any other frequency is undefined. This is akin to doing modal analysis in-situ.

A final method, to protect you, the analyst, is to repeat the survey at a later time, perhaps the next day. Never condemn a machine on a single reading. Machine vibration is always changing with load, sometimes transient, and sometimes I make a mistake in instrument setup. Better yet, have a colleague repeat the vibration survey with a separate measurement system. It is a certainty that the data will be attacked if it represents a financial loss to someone, or an embarrassment. Beware of attempts to “shoot the messenger.” It is always a healthy attitude to be suspicious of your own measurements, but at some point we must accept it as valid and proceed on. The repeat measurements provide this additional level of confidence.

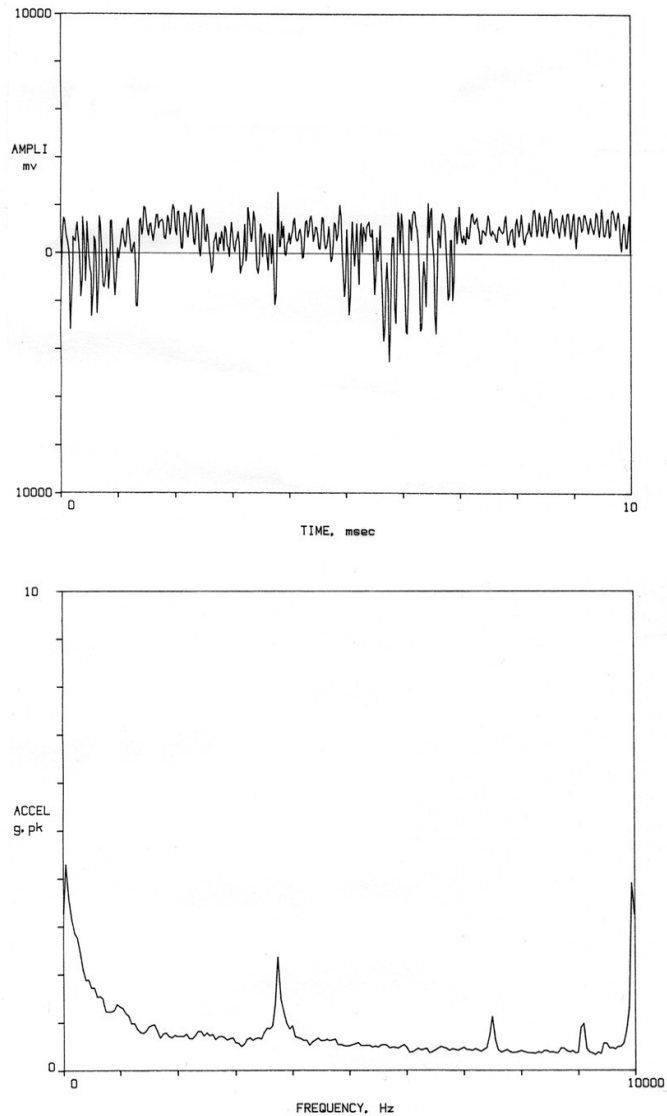


Figure 3. Intermittent Electrical Connection

Analysis of the Data

This is the human function of interpreting the squiggly lines. It is very subjective compared to the previous task of simply collecting numbers into a table. Two people can view the same data and come to different conclusions. There are diagnostic charts that aid in this process. Table 3 is an example. This chart is used to help identify the possible causes of vibration at specific frequencies. There are usually several possible causes for any particular frequency of vibration. The analyst should list the possible causes in order of probabilities and then, beginning with the most likely cause, do some further testing or information gathering to support or eliminate it. For example, there are many defects that can cause a high vibration at 1x rpm. These are:

- unbalance
- misalignment
- eccentricity
- bent shaft/bowed rotor
- soft foot
- reciprocating forces

Stepping through the possibilities, an alignment check with a shaft-measuring fixture can verify good alignment, a dial indicator can measure runouts for eccentricity and bent shafts, and a quick balance shot can determine if weight placement has any hope of correcting it. This leaves two remaining possibilities. Usually, vibration analysis is a process of elimination.

In addition to the diagnostic charts based on frequency, there are amplitude charts to judge the severity. Table 1 is an example. Figure 5 is another general chart for judging the amplitude and frequency jointly to determine if the vibration is anything to be concerned about. This chart has been circulating in the machine vibration community for at least three decades in various forms. It recognizes that displacement is more serious at the low frequencies because the limit lines parallel constant displacement. At high frequencies, acceleration is most significant in damage potential, and the limit lines slope downward along constant acceleration values above 200 Hz. In the mid range, velocity is a good parameter as a middle-of-the-road number useful for trending. Indeed, ANSI S2.41 defines vibration severity as overall RMS velocity from 10 to 1,000 Hz and provides a table defining values for good, satisfactory, unsatisfactory, and unacceptable. The chart in Figure 5 is in Log-Log coordinates and can be used to convert between displacement, velocity, and acceleration at any specific frequency.

Look for other information to support a diagnosis. This supporting information can be:

- noise from bearings or gears
- temperature at bearings
- oil contaminated with metal particles or other fluids
- wear indicators, such as excessive bearing clearance measured with a lift test
- runout measurements with a dial indicator
- visual inspection for looseness, dirt, cracks, or other abnormalities
- maintenance history

Machine-condition diagnosis based on vibration analysis alone is not a perfectly accurate technology. At best, it can be 80-percent successful. Supporting information raises the level of confidence. Expert diagnostic software programs are the least reliable.

Table 3. Common Machinery Faults

Cause	Frequency	Amplitude
Less than 1x rpm Beats Oil whirl Looseness Belts Resonance	Difference frequency Approx. 45% of 1x rpm $\frac{1}{2}, 1\frac{1}{2}, 2\frac{1}{2}, \text{etc.}$ $\pi(\text{rpm})(\text{pitch dia.})$ Discrete peaks	Comes and goes, caused by two machines running at almost the same speed. Applicable to high speed machines with plain bearings. Decrease with load. Note: Strobe light helps to see the defect. A serious condition with very high amplitudes.
At 1x rpm Unbalance Misalignment Eccentricity Bent Shaft Soft Foot Reciprocating	1 x rpm 1 x rpm + harmonics 1 x rpm 1 x rpm 1 x rpm 1 x rpm + harmonics	Mostly radial; a common fault High 2x and 3x; high axial; a common fault Looks like unbalance; cannot be corrected with weights Looks like unbalance; can be corrected with massive balance weights near the center. Dramatically decreases by loosening one hold down bolt More than 0.005 inches indicates misfiring.
Medium Frequencies Misalignment Motor Looseness Bearings Blades	2x, 3x, + harmonics 120 Hz + harmonics $\frac{1}{2}, 1\frac{1}{2}, 2\frac{1}{2}, \text{etc.}$ FTF = 0.4 x rpm OR = 0.4 x rpm x N IR = 0.6 x rpm x N N = # of balls rpm x (no of blades)	High axial; changes with temperature; a common fault Stops immediately upon disconnecting power. Also causes 120 Hz sidebands at higher frequencies. Not usually destructive; an indication of the quality of construction. Present on all motors and transformers to some degree. Decreases with load High frequency shock pulses in time domain Benign
High Frequencies Gears Cavitation Bearing	rpm x (no of teeth) 3-5 kHz broadband Broadband	Sidebands at gear mesh frequency; 2x gear mesh usually larger Usually benign; pressurizing inlet helps High frequency shock pulses in time domain

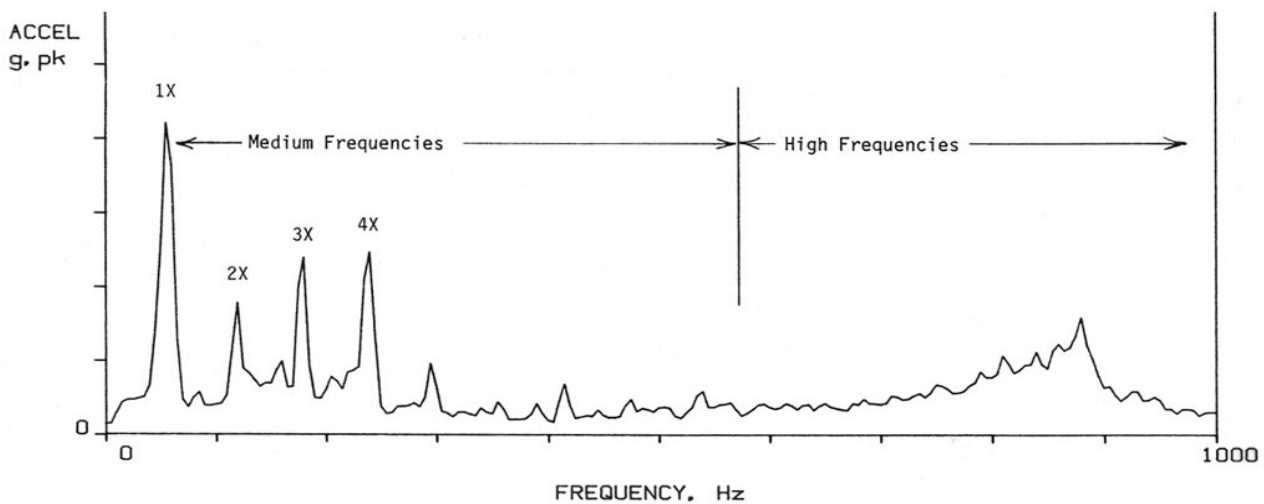


Figure 4. An Example FFT Spectrum of Common Machinery Vibration

Judgments

The owner of a sick machine usually wants to know if it will last until the next scheduled downtime. Providing this information with confidence is a shaky forecast, less reliable than predicting the weather that far in advance. Ideally, we would like to extract as much useful run time from a machine as possible and shut it down 2 minutes before it would have failed anyway, thus avoiding catastrophic damage. We would also like to have perfect weather and honest politics too. The world is not ideal, and machines fail at random times on their own schedule, with some advance warning sometimes. Predicting time to failure is an extrapolation from a trend chart developed from several measurements. Mathematically this

can be done if I had good previous measurements on this particular machine and I knew, with confidence, the level that it would fail at. Computer software can do this easily if the input numbers to the algorithm were any good. Suffice it to say that this process is better than a guess, but not by much. Here are some more useful judgment criteria that a real live person would have more success with.

First, not all machine vibration is bad. Some small amount of vibration is useful to overcome friction and to pump lubricants around. Resonance is usually painted as a bad character, but resonance in the wind will do no damage to the bearings. An example is a rooftop scrubber fan mounted on springs that shakes on a windy day at the spring natural frequency. Flexible supports allow more motion, which measures bad, but actually does less damage to the bearings because the oscillatory energy is converted into kinetic energy of motion rather than high contact stresses at the bearings. Vehicle wheels are a good example of this. They are flexibly mounted on springs which allows plenty of motion, but it does less damage to the tires or the road. We will see more compliant-mounted bearings in the future.

We measure motion, but we are really more interested in the stresses or forces causing that motion. We must judge the intensity of those forces based on motion measurements at some mass at some point. If motion is measured in acceleration, then force can be calculated with Newton's 2nd law, $F = ma$. This requires me to estimate the mass in motion that is being measured, and to assume that the mass is behaving as a rigid body. If motion is measured in displacement, then we can calculate force if we know something about the support stiffness that resists motion. The appropriate relationship is the stiffness equation, $F = kx$. In summary, one judgment strategy is to infer the internal forces from external motion measurements.

A second judgment criteria is the relative change. A 2x increase (or 6 dB) above a baseline normal level indicates that a significant physical change has occurred. A 5x increase is serious. Machine vibrations are rarely self-healing, but it has happened where a machine has worn itself a clearance and the vibration level dropped.

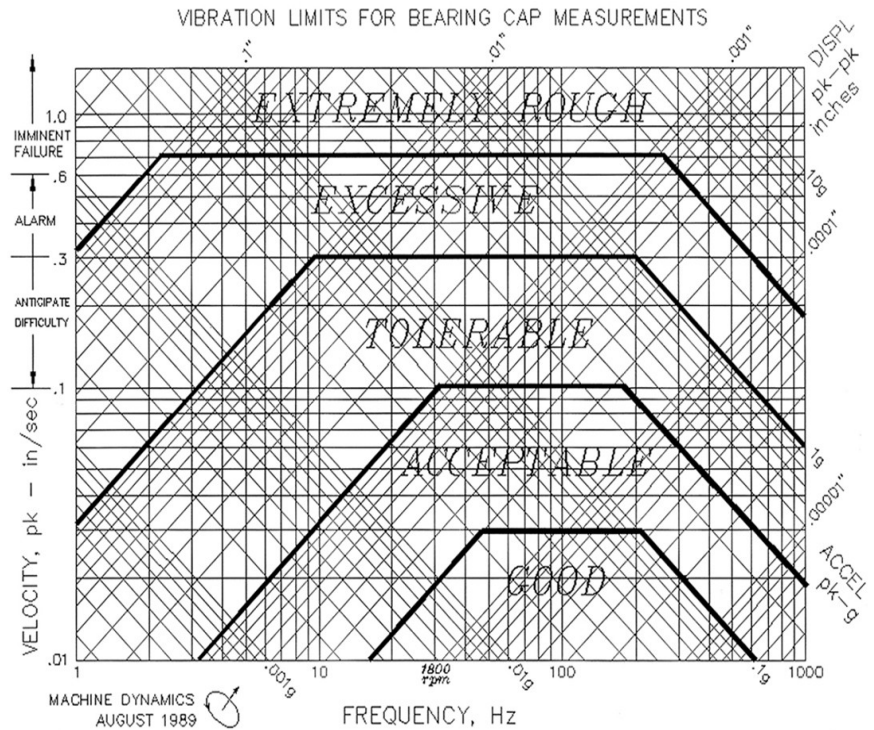


Figure 5. A General Vibration Specification Chart

A third judgment criteria is the rate of change. Slowly changing vibrations over a long time period (weeks) are wear related and are not cause for alarm if lubrication is present and the temperature is stable. It will wear more and become noisier, but it will still carry the load if lubrication is present. One strategy to nurse a machine to the next convenient outage is to grease it every day. A high, but stable, vibration amplitude is of concern but not an emergency if the temperature is stable. A rise in temperature at the bearings is cause for immediate action because friction is being generated with its pernicious side effect of thermal expansion and risk of seizure.

A step change in amplitude is symptomatic of an unstable bearing. Examination of the bearings and their supports is in order as soon as practical. A drop in frequency is bad news. It indicates structural softening such as cracks or joint loosening. Slow changes in amplitude from cold to hot running conditions are related to alignment of the shafts.

A fourth judgment criteria is operational condition. The load level has a dramatic effect on vibration levels, especially electrical machines such as generators. It is usually assumed in analysis that the machine has no operational problems, such as:

- misfiring of engines
- single phasing of motors
- poor flow conditions of fans and pumps

If no other cause of vibration is obvious, it may be time to re-examine the operating condition of the machine.

A fifth judgment criteria is to visualize the flow of vibratory energy. We can establish the source of energy from the frequency signature. This tells me where it is produced and I know where it is being measured. What lies in between? Visualize the path of vibratory energy and what components are exposed to those oscillating forces. Finally, where is this vibratory energy dissipated?

A sixth judgment criteria is how long the machine needs to run before a replacement comes along. Vibration is an accumulated wear mechanism that causes fatigue failure over some time period or number of cycles. One purpose for reducing vibration is to extend the life of machines. If this particular machine needs to run only two more weeks before it will be replaced, then higher vibration levels can be tolerated for a short time with low risk of failure.

A final note on judgment is who makes the stop/go decision. Vibration analysts should not make that decision. The production manager should have that authority, with vibration as one input, because he/she needs to consider other factors, such as:

- Are repair parts on hand?
- Is skilled labor available to do the repair?
- What is the impact on production?
- What are the risks and consequences of an early unexpected failure?

Sometimes, machines will be sacrificed because the operational requirements are more valuable than one machine. The analyst provides early warning, trending, and diagnostic information for someone else to make the stop/go decision.

Root-Cause Analysis

Machine vibration has several categories of causes that are discovered sometimes after repair, but it is useful now to review them to gain more confidence in the diagnosis. The major categories are:

- design defects
- manufacturing defects
- operational stresses
- maintenance actions
- aging

Design defects are mostly structural related with active resonances built-in because of improper sizing and proportioning of the parts. Statically, the structure is O.K., but is dynamically weak. This is not discovered until the machine is energized and brought up to speed. This is more common than it should be, but designers are not well equipped to predict or test for natural frequencies. In addition, the owner's foundation or base has a significant effect on natural frequencies, which the designer has little control over. Hence, resonances are best detected during startup testing and corrected on-site with strategic stiffeners added.

Manufacturing defects are built-in during the casting, machining, heat-treating, and assembly processes. They are latent defects that may show up in the first 24-hours of running, or they may not be obvious during the run-in period, rather appearing years later. The machine does not survive to a normal life expectancy. Vibration may or may not be present. An example is residual stresses in a shaft that gradually distorts the shaft over a period of years. Manufacturing defects are difficult to control, impossible to predict, and elusive to fix. The best strategy to deal with both design defects and manufacturing defects is to insist on startup vibration testing with limits of acceptability in accordance with Table 1.

Excessive operational stresses can develop due to material buildup or erosion, that changes the balance condition, or thermal expansion that changes component alignment. Both of these cause high dynamic loads at the bearings which lead to accelerated wearout. These defects are easily detected with periodic vibration measurements and there are well-established methods to correct them on site.

Maintenance actions, or inactions, are the most common cause of machine failure. It is well known in the repair business that a machine never goes back together the same way. Some of this is due to rough handling, but some is simply the fact that field repair is less controlled than the original factory build. The field environment is darker, dirtier, and less-precise tooling is available to control fits and alignments. The repair is usually rushed by management. It is surprisingly difficult to install a bearing into an aluminum housing in the field and not get it crooked. The first question to ask in vibration analysis is “What recent maintenance activity has occurred on this machine?” Other maintenance activities that affect vibration are:

- excessive localized heating, like welding on a shaft
- too-high belt tension
- shaft, or bearing, misalignment
- substandard replacement parts
- coupling, or other component, binding
- lack of lubrication
- loose hardware
- replacing hardware with different weights that affect balance
- re-assembling hardware in different orientations (also affects balance)
- hammering on a bearing
- unclean, or burred, precision-machine surfaces

Aging effects can only be detected with long-term vibration monitoring. The two dominant aging effects are residual stress relaxation and softening of structural joints. The residual stresses left behind in machine components will always relieve themselves over time. This process is accelerated at higher temperature. Shafts, being long and slender components, are particularly vulnerable to bowing. The symptoms are an increase in 1x-rpm balance condition and beating up of the bearings. Bearing replacements do not restore the original smooth-running condition, and mass balancing is unsuccessful, until the shaft is replaced.

All joints soften over time, and joints are the weak links in any structure. The subtle symptom of this is lowering of the natural frequencies. This is usually first detected with high vibration when the lowest natural frequency drops down into the operating-speed range of the machine.

In the professional field of machine vibration analysis, we are all guilty, at one time or another, of making false assumptions initially that machines are well designed, well manufactured, well operated, well maintained, and that nothing changes with time. Some day we may find that perfect planet out there, where Murphy has not taken up residence yet.

Corrective Methods

The good news is that almost all machine vibration problems can be corrected in place. The corrective methods are well established and are described in depth in other writings. They are listed here to close this discussion.

- Disassembly, visual inspection, cleaning, and re-assembly can fix some elusive problems without knowing what was really done because it may go back together differently.
- Bearing replacement
- Identifying other bad parts and replacing them
- Mass balancing
- Alignment
- Lubrication. Just greasing noisy bearings can quiet them, but changing the lubrication schedule can extend their lives.
- Structural stiffening to raise natural frequencies.
- Mass loading and stiffening can reduce any measured vibration. They will lower motion, but this may increase local stresses at the bearings resulting in faster bearing wear. This is to be used only as a last resort when nothing else works and measured motion must be lowered.

Finally, a few machines are still generating excessive vibration, the cause has not been discovered nor corrected, and they have not shaken themselves apart yet. Some machines are just rough characters and it is not necessary nor desirable to retrain them. As long as the vibration amplitude remains stable, it is safe to continue to operate at elevated levels, thus avoiding repair cost and downtime. Regular vibration monitoring has allowed machines to operate longer into the wearout cycle without fear of failure. Knowledge is power.