Interpreting The Severity Charts

When one examines the displacement severity charts in Figures 2-7, 2-8 and 2-9, it should become apparent that there is no **absolute** vibration limit above which the machine will fail and below which the machine will run indefinitely.

What's the difference between "GOOD" and "SMOOTH", for example, or "ROUGH" and "SLIGHTLY ROUGH"? It is impossible to establish absolute vibration limits. However, in setting up a predictive maintenance program, it is necessary to establish some severity criteria or limits above which action will be taken. The charts in Figures 2-7, 2-8 and 2-9 apply to general types of machinery such as fans, blowers, pumps and motors. For these types of machines, vibration levels in the "GOOD" region or below generally indicate satisfactory operation and no significant problems. Machines in this category can be scheduled for routine vibration checks until such time that excessive vibration or a significant increase in normal vibration is detected.

General machines with vibration levels in the "FAIR" and "SLIGHTLY ROUGH" regions typically have minor problems that would warrant an analysis to determine the cause for correction at the earliest convenient opportunity. In the interim, the interval of periodic checks should be reduced to maintain closer surveillance. Of course, preparations for correction such as obtaining needed parts, tools and scheduling of repair personnel should be carried out as well, to keep repair downtime to an absolute minimum.

Machines with vibration levels in the "ROUGH" region or above should be analyzed immediately for cause determination and shut down at the earliest opportunity for correction.

Of course, not all machines can be evaluated in the same way. Machine tools, for example, usually require much lower levels of vibration than general machines in order to manufacture quality parts in terms of surface finish and to maintain dimensional tolerances. The table in Figure 2-10 shows vibration displacement levels typical of various types of machine tools. As noted on the table, these values merely indicate the range within which satisfactory parts have been produced and will vary depending on size and finish tolerances.

GENERAL MACHINERY VIBRATION SEVERITY CHART

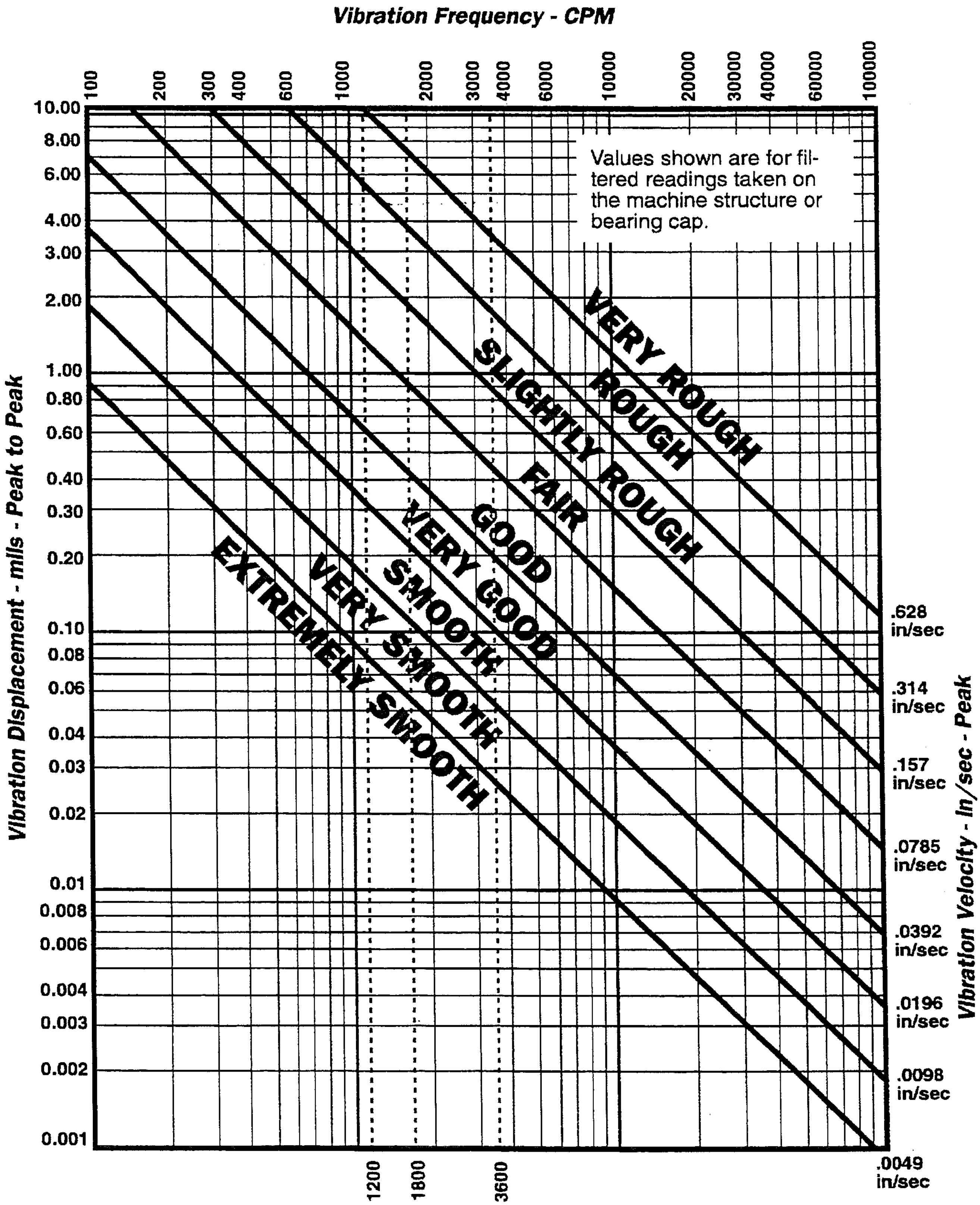


Figure 2-8. General Machinery Vibration Severity Chart. (English units)

METRIC MACHINERY VIBRATION SEVERITY CHART

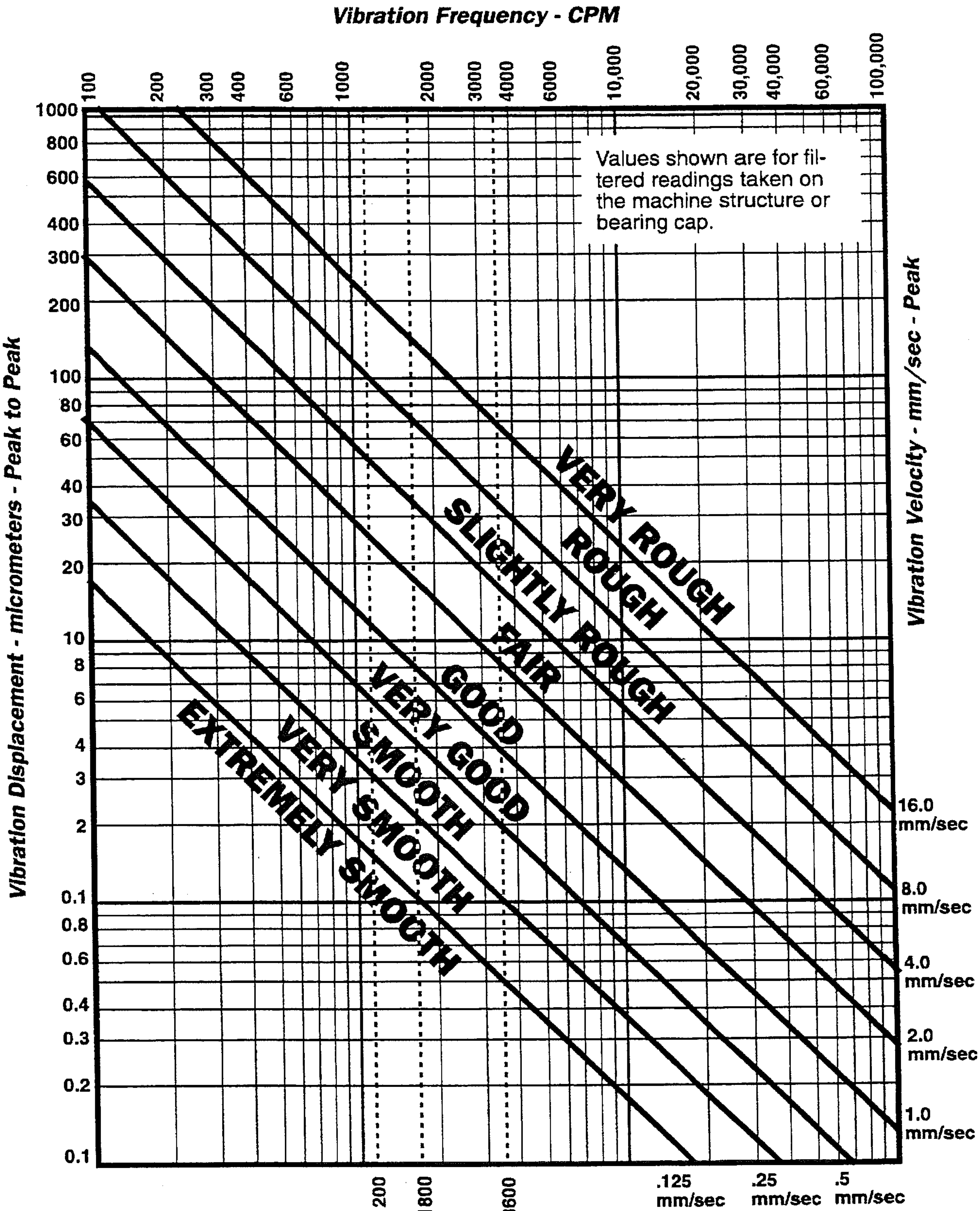


Figure 2-9. General Machinery Vibration Severity Chart. (Metric Units)

Machine-Tool Vibration Tolerance Table

The chart below can be used as a guide for determining vibration tolerances for grinders and other machine tools where vibration can affect the quality of a finished product.

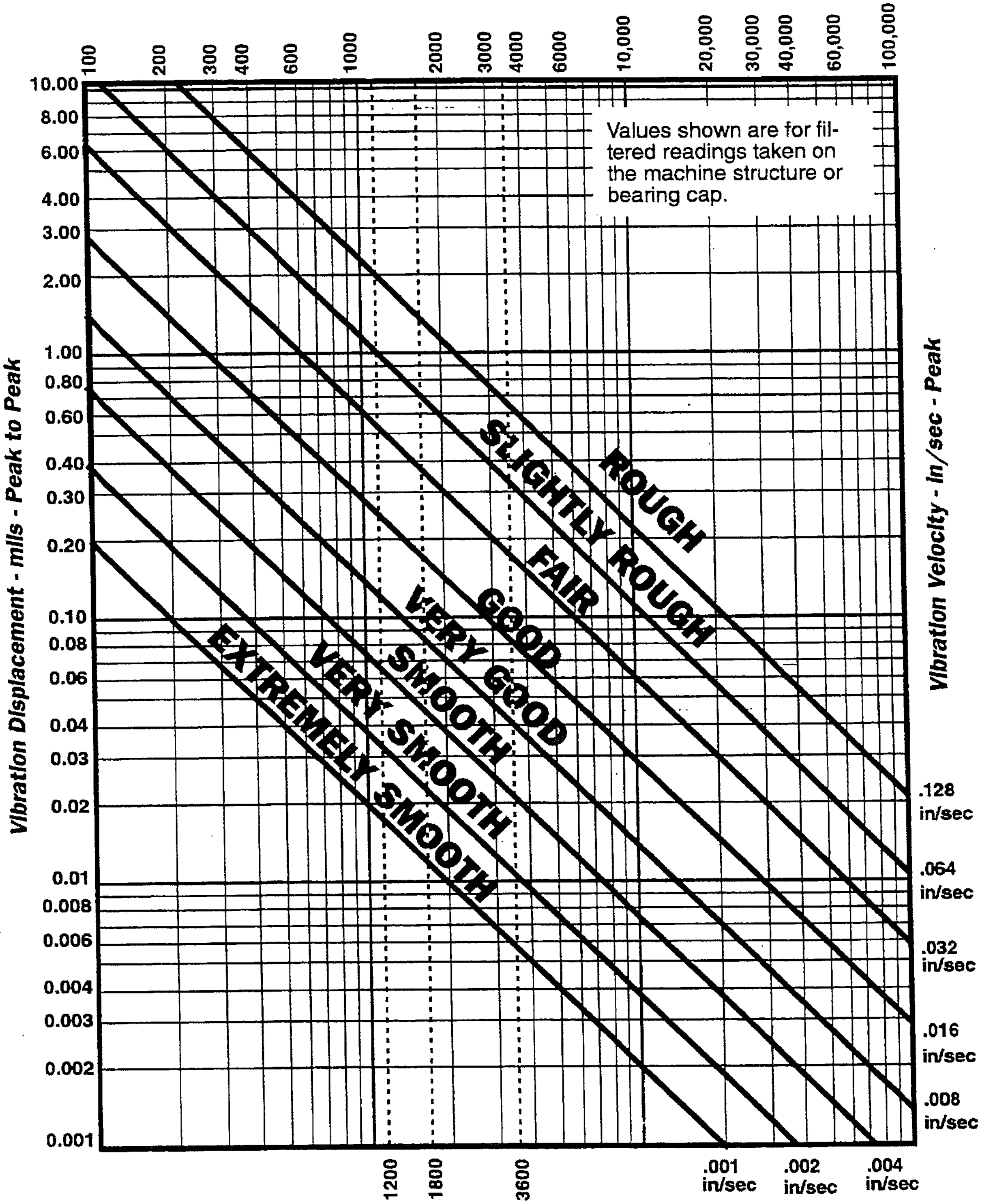


Figure 2-10. Typical vibration displacement tolerances for machine tools.

There are many factors that determine the normal or inherent vibration characteristics of a machine. How and where the machine is mounted is one consideration. In most cases, a machine that is bolted to a rigid base will have inherently less vibration than one that is mounted on spring isolators or rubber pads. Machines such as hammer mills or rock crushers may have much higher levels of normal vibration than other machines, simply because of what they do. When it is not known whether a machine's vibration level is normal or indicative of developing trouble one can:

1. Compare the machine's vibration characteristics with other identical or similar machines. If a machine has a level of vibration 2 or 3 times higher than that of similar machines, some problem is usually indicated, and a through analysis should be carried out to pinpoint the cause for correction.
2. Check the machine's vibration on a frequent and regular basis. Normally, machines that have significant problems will show signs of deterioration through increasing levels of vibration. If this is the case, a through analysis should be performed at the earliest opportunity to pinpoint the cause for correction. On the other hand, if the vibration levels remain unchanged over a long period of time, the vibration may be considered as normal or inherent for this type of equipment.

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. To evaluate each machine's displacement and frequency characteristics using severity charts such as those in Figures 2-7, 2-8 and 2-9 would be an extremely time-consuming task. 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. For example, assume that a machine operating at 1800 RPM has a vibration displacement of 1 mil peak-to-peak at a frequency of 1800 CPM due to unbalance. According to the chart in Figure 2-8, this would be considered "FAIR". In addition, assume that the machine also has a vibration displacement of 0.5 mils at a frequency of 3600 CPM (2 x RPM) due to misalignment. This vibration also would be considered "FAIR" according to the chart in Figure 2-8. Although one might be inclined to judge the condition of the machine as "FAIR", this is not the case. 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 at which the object is deflected (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 at which a machine or machine component is moving as it undergoes oscillating motion. Figure 2-11 shows the time waveform of the vibrating spring-mass system from Figure 2-1. 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.

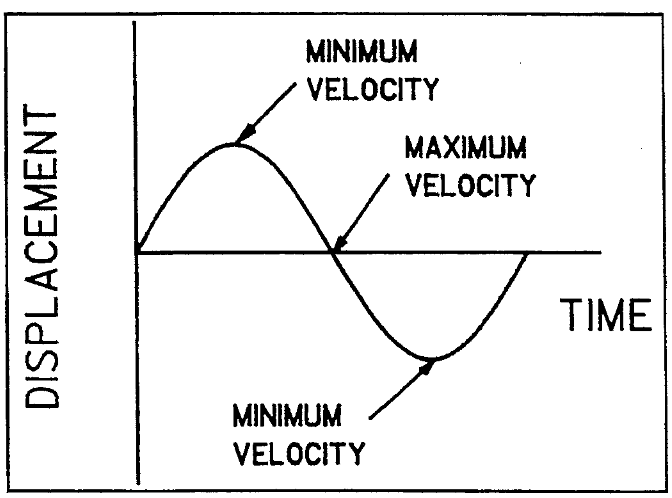


Figure 2-11. Velocity of a vibrating object.

The fact that vibration velocity is a direct indicator of fatigue and vibration severity is clearly indicated by the General Machinery Vibration Severity Charts, Figures 2-8 and 2-9. Note that the diagonal lines that separate the different regions of severity are **constant velocity values.** For example, the line dividing the "ROUGH" and "VERY ROUGH" regions has a velocity value of 0.628 in/sec-peak (16 mm/sec-pk). Thus, a machine having a measured vibration velocity in excess of 0.628 in/sec-peak (16 mm/sec-pk), would be considered "VERY ROUGH", regardless of the vibration frequency.

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.**

Although the velocity values assigned to the diagonal lines separating the zones of severity on the General Machinery Vibration Severity Charts in Figures 2-8 and 2-9 provide a reasonable guideline for evaluating vibration velocity measurements, the tables in Figures 2-12 (English units) and 2-13 (Metric units) provide an even better guide since they take into consideration specific machine types, types of mountings, and how the machine is driven (direct coupled, belt driven, gear driven, etc.). These tables were developed by Technical Associates Of Charlotte, Inc. (2), and represent nearly two decades of experience with literally thousands of machines.

These charts are not intended to be used for establishing vibration acceptance criteria for rebuilt or newly installed machines. They are to be used to evaluate the general or "overall" condition of machines that are already installed and operating in service. For those setting up a predictive maintenance program, lacking experience or historical data, this table will serve as an excellent guide to get started.

Chapter 4 - Measurement Parameters and Alarm Values

SUGGESTED OVERALL ALARMS BY MACHINE TYPE - IMPERIAL
(Peak, Overall Velocity, in/sec.)

MACHINE TYPE	GOOD	FAIR	ALARM
Cooling Tower Drives	0 -.375	.375 -.15	.600
Compressors			
Reciprocating	0 -.325	.325 -.500	.500
Rotary Screw	0 -.275	.275 -.425	.425
Centrifugal with or without External Gearbox	0 -.200	.200 -.300	.300
Centrifugal - Integral Gear (Axial Meas.)	0 -.200	.200 -.300	.300
Centrifugal - Integral Gear (Radial Meas.)	0 -.150	.150 -.250	.250
Blowers Fans			
Lobe -Type Rotary	0 -.300	.300 -.450	.450
Belt-Driven Blower	0 -.275	.275 -.425	.425
General Direct Drive Fans	0 -.250	.250 -.375	.375
Primary Air Fans	0 -.250	.250 -.375	.375
Large Forced Draft Fans	0 -.200	.200 -.300	.300
Large Induced Draft Fans	0 -.175	.175 -.275	.275
Shaft-Mounted Integral Fan	0 -.175	.175 -.275	.275
Motor/Generator Sets			
Belt-Driven	0 -.275	.275 -.425	.425
Direct Coupled	0 -.200	.200 -.300	.300
Chillers			
Reciprocating	0 -.250	.250 -.400	.400
Centrifugal (Open-Air)	0 -.200	.200 -.300	.300
Centrifugal (Hermetic)	0 -.150	.150 -.225	.225
Large Turbine/Generators			
3600 RPM Turbine/Generators	0 -.250	.250 -.375	.375
3600 RPM Turbine/Generators	0 -.250	.250 -.375	.375
1800 RPM Turbine/Generators	0 -.175	.175 -.275	.275
Centrifugal Pumps			
Vertical Pumps (12' - 20')	0 -.375	.375 -.600	.600
Vertical Pumps (8' - 12' Height)	0 -.325	.325 -.500	.500
Vertical Pumps (5' - 8' Height)	0 -.250	.250 -.400	.400
Vertical Pumps (0' - 5' Height)	0 -.200	.200 -.300	.300
General Purpose Horizontal	0 -.200	.200 -.300	.300
Boiler Feed Pumps	0 -.200	.200 -.300	.300
Hydraulic Pumps	0 -.125	.125 -.200	.200

SUGGESTED OVERALL ALARMS BY MACHINE TYPE - IMPERIAL
(Peak, Overall Velocity, in/sec.)

MACHINE TYPE	GOOD	FAIR	ALARM
Machine Tools			
Motor	0 -.100	.100 -.175	.175
Gearbox Input	0 -.150	.150 -.225	.225
Gearbox Output	0 -.100	.100 -.175	.175
Spindles			
Roughing Operations	0 -.075	.075 -.125	.125
Machine Finishing	0 -.050	.050 -.075	.075
Critical Finishing	0 -.030	.030 -.050	.050

CHART NOTES:

1. Assuming machine speed = 500 to 600,000 RPM.
2. Assuming measurements by accelerometer or velocity pickup as close as possible to bearing housing.
3. Assuming machine not mounted on vibration isolators (for isolated machinery - set alarm 30% to 50% higher)
4. Set motor alarms same as that for the particular machine type, unless otherwise noted.
5. Set alarms on individual external gearbox 25% higher than that for a particular machine type.

Figure 2-12. Criteria for evaluating overall condition rating using overall velocity. (in/sec-peak)

Chapter 4 - Measurement Parameters and Alarm Values

SUGGESTED OVERALL ALARMS BY MACHINE TYPE - METRIC
(Peak, Overall Velocity, mm/sec.)

MACHINE TYPE	GOOD	FAIR	ALARM
COOLING TOWER DRIVES	0 -9.5	9.5 -15	15
COMPRESSORS			
Reciprocating	0 -8	8 -13	13
Rotary Screw	0 -7	7 -11	11
Centrifugal with or without External Gearbox	0 -5	5 -7.5	7.5
Centrifugal - Integral Gear (Axial Meas.)	0 -5	5 -7.5	7.5
Centrifugal - Integral Gear (Radial Meas.)	0 -4	4 -6.5	6.5
BLOWERS FANS			
Lobe-Type Rotary	0 -7.5	7.5 -11.5	11.5
Belt-Driven Blower	0 -7	7 -11	11
General Direct Drive Fans	0 -6.5	6.5 -9.5	9.5
Primary Air Fans	0 -6.5	6.5 -9.5	9.5
Large Forced Draft Fans	0 -5	5 -7.5	7.5
Large Induced Draft Fans	0 -4.5	4.5 -7	7
Shaft-Mounted Integral Fan	0 -4.5	4.5 -7	7
MOTOR/GENERATOR SETS			
Belt-Driven	0 -7	7 -11	11
Direct Coupled	0 -5	5 -7.5	7.5
CHILLERS			
Reciprocating	0 -6.5	6.5 -10	10
Centrifugal (Open-Air)	0 -5	5 -7.5	7.5
Centrifugal (Hermetic)	0 -4	4 -6	6
LARGE TURBINE/GENERATORS			
3600 RPM Turbine/Generators	0 -6.5	6.5 -9.5	9.5
3600 RPM Turbine/Generators	0 -6.5	6.5 -9.5	9.5
1800 RPM Turbine/Generators	0 -4.5	4.5 -7	7
CENTRIFUGAL PUMPS			
Vertical Pumps (12' - 20')	0 -9.5	9.5 -15	15
Vertical Pumps (8' - 12' Height)	0 -8	8 -13	13
Vertical Pumps (5' - 8' Height)	0 -6.5	6.5 -10	10
Vertical Pumps (0' - 5' Height)	0 -5	5 -7.5	7.5
General Purpose Horizontal	0 -5	5 -7.5	7.5
Boiler Feed Pumps	0 -5	5 -7.5	7.5
Hydraulic Pumps	0 -3	3 -5	5

SUGGESTED OVERALL ALARMS BY MACHINE TYPE - METRIC
(Peak, Overall Velocity, mm/sec.)

MACHINE TYPE	GOOD	FAIR	ALARM
MACHINE TOOLS			
Motor	0 -2.5	2.5 -4.5	4.5
Gearbox Input	0 -4	4 -6	6
Gearbox Output	0 -2.5	2.5 -4.5	4.5
SPINDLES			
Roughing Operations	0 -2	2 -3	3
Machine Finishing	0 -1	1-2	2
Critical Finishing	0 -.5	.5 -1	1

CHART NOTES:

1. Assuming machine speed = 500 to 600,000 RPM.
2. Assuming measurements by accelerometer or velocity pickup as close as possible to bearing housing.
3. Assuming machine not mounted on vibration isolators (for isolated machinery - set alarm 30% to 50% higher)
4. Set motor alarms same as that for the particular machine type, unless otherwise noted.
5. Set alarms on individual external gearbox 25% higher than that for a particular machine type.

Figure 2-13. Criteria for overall condition rating using overall velocity. (mm/sec-peak)

The following is a general interpretation of the charts:

GOOD: Machines with overall vibration velocity levels in the GOOD range may have minor problems. However, at this level, the problems are not normally severe enough to warrant shutting the machines down for further corrections. These machines should simply be checked on a regularly scheduled basis (weekly, monthly, etc.) to detect any significant increases in vibration. A "baseline" vibration frequency analysis should be performed on these machines to identify their normal vibration characteristics. This information will prove invaluable in pinpointing the cause when problems do develop.

FAIR: Machines with overall vibration velocity levels in the FAIR range have somewhat more severe problems, but generally, not severe enough to warrant an immediate shutdown for correction. Since machine deterioration usually progresses more rapidly at these vibration levels, periodic vibration checks should be made 2 to 3 times more frequently than the normal check interval. In other words, if a monthly check is scheduled for machines with vibration levels in the GOOD range, machines in the FAIR range should be checked at least 2 to 3 times a month to avoid catastrophic failure.

A vibration analysis should also be performed on machines that fall in the FAIR range to not only establish a "baseline" for future analysis, but to identify specific problem(s) causing the vibration. If a convenient opportunity is available to shut the machine down, needed corrections should be made to prolong machine life.

ALARM: Lacking any past history, the ALARM levels given in the table serve as realistic starting points for a predictive maintenance program. Machines that fall in this category should be thoroughly analyzed to pinpoint the cause or causes of vibration and a shutdown scheduled for correction at the earliest opportunity.

Until such time that a shutdown for correction can be scheduled, periodic vibration checks should be made even more frequently than for those machines in the FAIR category. For machines critical to a plant's operation, even daily vibration checks may be in order to prevent a catastrophic failure. As one vibration technician once said, **"The worse things get, the quicker they get worse."**

Machines with vibration velocity levels well above the ALARM level should be thoroughly analyzed to identify the problems and scheduled for **immediate** shutdown and correction. Experience has shown time and time again that continued operation at such high levels of vibration typically results in catastrophic, costly failure. Although some machines may continue to operate at vibration levels well above ALARM, such cases fall in the minority and continued operation is simply a **gamble**.

For machines that do not fall into one of the machine descriptions listed in Figures 2-12 and 2-13, the "Overall Velocity Guidelines For Vibration Severity" presented in Figure 2-14 can be used to provide a realistic starting point.

OVERALL VELOCITY GUIDELINES FOR VIBRATION SEVERITY

Overall Vibration Velocity Pk	Classification	Description
.6 in/s & up (15 mm/s & up)	VERY ROUGH	***Severe vibration. Potentially unsafe.*** Make immediate detailed vibration analysis to identify trouble. Excessive vibrations may cause oil-film breakdown. Consider shutdown to avoid in-service failure.
.3 to .6 in/sec (8 to 15 mm/s)	ROUGH	***Potentially damaging vibration.*** Make detailed vibration analysis to identify trouble. Rapid wear expected. Make more frequent periodic checks. Schedule for repair.
.2 to .3 in/sec (5 to 8 mm/s)	SLIGHTLY ROUGH	***Faults likely.*** Make detailed vibration analysis. Continue periodic checks. Schedule repair as necessary.
.1 to .2 in/s (3 to 5 mm/s)	AVERAGE	***Minor faults.*** Continue routine periodic checks. Watch for increase.
.05 to .1 in/s (1 to 3 mm/s)	SMOOTH	***Well Balanced.*** Typical of well balanced, well aligned equipment. Make routine periodic checks.
0 to .05 in/s (0 to 1 mm/s)	VERY SMOOTH	***Exceptional.*** Extremely well balanced, well aligned equipment. Make routine periodic checks.

Figure 2-14. Overall velocity guidelines for vibration severity.

As stated earlier, establishing absolute vibration tolerances is simply not possible. 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

Figure 2-11 showed that 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 in Figure 2-15, 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.

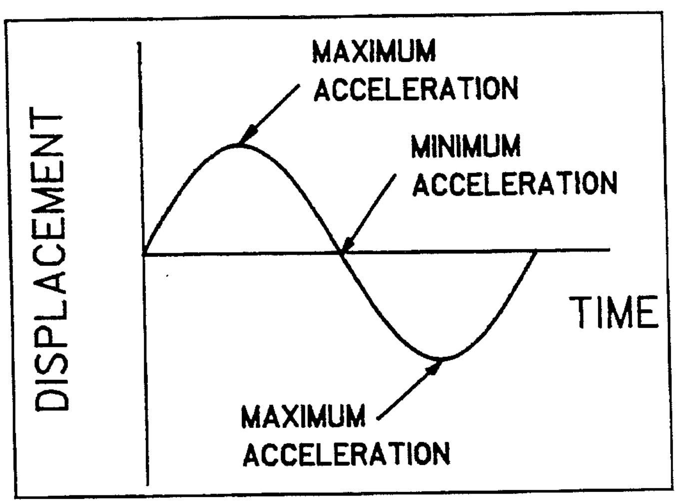


Figure 2-15. Acceleration (G's) of a vibrating part.

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. The chart in Figure 2-16 has been developed after many years of experience on all types of industrial machinery. 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. For example, from the chart in Figure 2-16, a vibration acceleration of 1.0 G occurring at a frequency of 18,000 CPM (300 Hz) would fall in the SLIGHTLY ROUGH range, whereas a vibration of 1.0 G at a frequency of 600,000 CPM (10,000 Hz) would fall between the GOOD and VERY GOOD regions of the chart.

It should also be noted that the vibration acceleration severity chart in Figure 2-16 only covers high frequencies of vibration—above 18,000 CPM. The reason for this will be explained in the following sections.

VIBRATION ACCELERATION GENERAL SEVERITY CHART

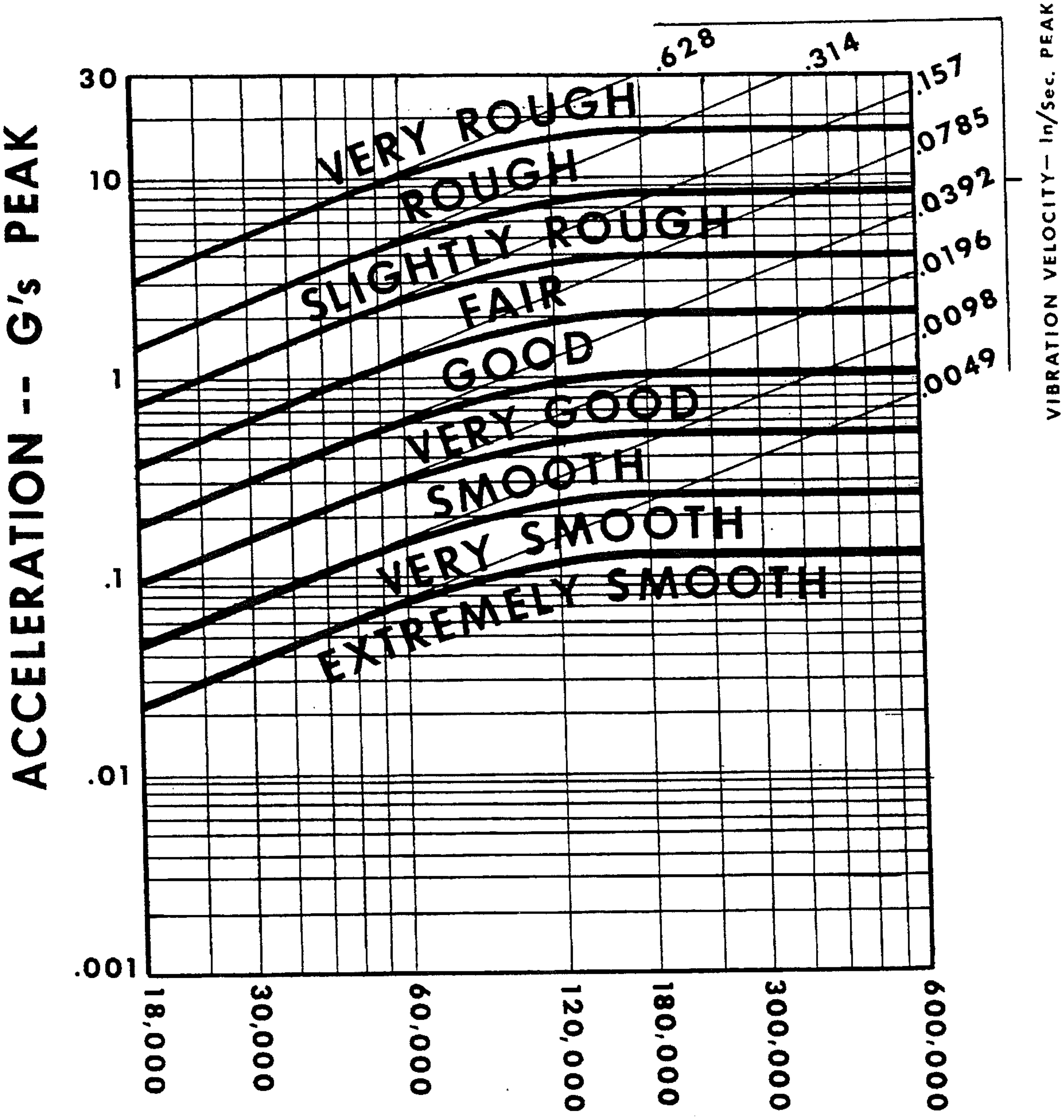


Figure 2-16. Vibration acceleration (G's) severity chart.

Conversion Of Measurement Parameters

For simple vibration, consisting of only one frequency, the values of displacement, velocity and acceleration are all mathematically related as shown by the conversion formulas in Figure 2-17. For example, if the displacement and frequency of a vibration are known, the vibration velocity or vibration acceleration can simply be calculated using the appropriate formula. These conversion formulas **do not** apply to complex vibration.

ENGLISH UNITS

Where: D = Peak-To -Peak Displacement (Mils Pk-Pk)
V = Peak Velocity (In/Sec-Pk)
A = Peak Acceleration (G's-Pk)
F = Frequency (CPM)

$$V = \frac{DF}{19{,}100} \qquad D = \frac{19{,}100\ V}{F}$$

$$V = \frac{3690\ A}{F} \qquad A = \frac{VF}{3690}$$

$$A = \frac{DF^2}{70{,}470{,}910} \qquad D = \frac{70{,}470{,}910}{F^2}$$

METRIC UNITS

Where: D = Peak-To -Peak Displacement (Mils Pk-Pk)
V = Peak Velocity (In/Sec-Pk)
A = Peak Acceleration (G's-Pk)
F = Frequency (CPM)

$$V = \frac{DF}{19{,}100} \qquad D = \frac{19{,}100\ V}{F}$$

$$V = \frac{93{,}640\ A}{F} \qquad A = \frac{VF}{93{,}640}$$

$$A = \frac{DF^2}{1{,}790{,}000{,}000} \qquad D = \frac{1{,}790{,}000{,}000\ A}{F^2}$$

Figure 2-17. Vibration parameter conversion formulas.

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, in fact, due to fatigue, which is directly related to vibration velocity, there are two other causes or "mechanisms" of machinery failure—**stress and force**—that are directly related to vibration displacement and acceleration respectively.

When To Use Displacement As An Indicator Of Stress Problems

The fatigue failure of machine components from repeated cycles of flexing and the direct relationship between vibration velocity and fatigue have been explained in the preceding sections of this Chapter. 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)**. For example, consider a machine that has a vibration displacement of 100 mils occurring at a frequency of only 50 CPM. Using the conversion formula in Figure 2-17, the corresponding vibration velocity is found to be only 0.26 in/sec.

$$\text{Velocity (in/sec)} = \frac{\text{D (mils)} \times \text{F(CPM)}}{19{,}100}$$

$$\text{Velocity (in/sec)} = \frac{100 \text{ mils} \times 50\text{(CPM)}}{19{,}100}$$

$$\text{Velocity (in/sec)} = \frac{5{,}000}{19{,}100}$$

$$\text{Velocity (in/sec)} = 0.26 \text{ in/sec}$$

According to the severity guidelines in Figures 2-8, 2-12 and 2-14, a vibration velocity of only 0.26 in/sec would probably be considered between the FAIR and SLIGHTLY ROUGH regions and not a cause for immediate concern. However, it must be remembered that the machine is being deflected **100 mils which is 0.1 inch**. Under these conditions, failure will most likely occur due to stress (displacement) rather than fatigue (velocity). For this reason, whenever it is anticipated that vibration frequencies may be present at frequencies below 600 CPM (10 Hz), measurements of vibration displacement are recommended.

When To Use Vibration Velocity To Detect Fatigue Problems

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.

When To Use Vibration Acceleration To Detect Force Problems

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. To illustrate, assume that a machine has a measured vibration velocity of 0.25 in/sec-pk occurring at a frequency of 600,000 CPM (2000 Hz), perhaps due to a gear problem. From the conversion formulas in Figure 2-17, the resultant vibration acceleration is found to be over 40 G's.

$$\text{Acceleration (G's)} = \frac{\text{V (in/sec) x F(CPM)}}{3{,}690}$$

$$\text{Acceleration (G's)} = \frac{\text{0.25 in/sec x 60,000CPM}}{3{,}690}$$

$$\text{Acceleration (G's)} = \frac{150{,}000}{3{,}690}$$

$$\text{Acceleration (G's)} = \text{40.65 G's}$$

Again, according to the severity guidelines in Figures 2-8, 2-12 and 2-14, a vibration velocity of only 0.25 in/sec would be considered within the FAIR to SLIGHTLY ROUGH regions. However, according to the vibration acceleration severity chart in Figure 2-16, the 40 G's is **"off the chart"** and would be considered **EXTREMELY ROUGH**. In this case, failure will most likely result from extreme forces and not stress or fatigue. 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.

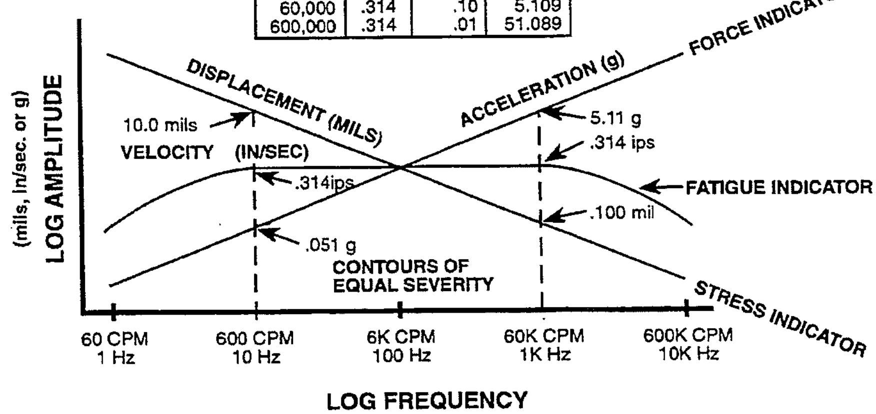
Because of the importance of vibratory forces at high frequencies, vibration acceleration measurements (G's) are recommended whenever vibration frequencies above **120,000 CPM (2000 Hz)** are anticipated. Probably the most common source of such high frequencies are gear-mesh frequencies and harmonics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

Contours Of Equal Severity

Perhaps the best way to summarize the applications for displacement, velocity and acceleration measurements is to examine the "Contours Of Equal Severity" chart in Figure 2-18. (2) This chart shows the frequency ranges over which each parameter of vibration amplitude best indicates the severity of vibration.

From the chart, it can be seen that at very low frequencies, below 600 CPM, vibration displacement is, by far, the best indicator of vibration severity from a stress standpoint. This is not to say that velocity or even acceleration could not be used at frequencies below 600 CPM; however, the allowable levels of velocity and acceleration below 600 CPM would be considerably lower than they would at much higher frequencies. For example, according to the chart, a vibration acceleration of only 0.051 G's at a frequency of 600 CPM would be equal in severity to 5.11 G's at a frequency of 60,000 CPM.

Similarly, although vibration acceleration is obviously the best indicator of severity from a force standpoint at high frequencies, (above 60,000 CPM), this does not mean that velocity and displacement could not be used. However, according to the chart, a vibration displacement of only 0.1 mil would be equal in severity to a vibration displacement of 10.0 mils at a frequency of 600 CPM. The chart also shows that the most linear indicator of vibration severity over the frequency range from 600 CPM to 60,000 CPM (10 Hz to 1,000 Hz) is velocity. **Although this chart tends to indicate that vibration acceleration should be used for frequencies above 60,000 CPM (1,000 Hz), experience has proven that vibration velocity is quite useful at even much higher frequencies and its use is recommended to at least 120,000 CPM (2,000 Hz).** In fact, many experienced vibration technicians have reported using vibration velocity measurements for vibration frequencies as high as 240,000 CPM (4,000 Hz) with excellent results.



F (cpm)	V	D	A
60	.314	100.00	.005
600	.314	10.00	.051
6,000	.314	1.00	.511
60,000	.314	.10	5.109
600,000	.314	.01	51.089

$$V = \frac{\pi D F}{60,000} \qquad D = \frac{60,000V}{\pi F} \qquad A = \frac{D F^2}{70,470,910} \qquad D = \frac{70,470,910 A}{F^2}$$

$$V = \frac{3,690 A}{F} \qquad A = \frac{VF}{3,690}$$

Where: A = Peak Acceleration (g)
V = Peak Velocity (in/sec)
D = Peak-Peak Displacement (mils)
F = Frequency (CPM)

Figure 2-18. Contours of equal severity.

Vibration Frequencies Detected By Displacement, Velocity And Acceleration

Another important consideration when selecting vibration displacement, velocity and acceleration for measurement is the problem-related vibration frequencies which can actually be **detected** by each amplitude parameter. This is especially important when dealing with machines that have complex vibration with a very wide range of possible problem-related vibration frequencies. This can best be illustrated by examining comparative displacement, velocity and acceleration **"spectrums"** obtained on an actual machine. Vibration spectrums, also called vibration **"signatures"** or **"FFT's"**, are obtained with a vibration frequency analyzer or data collector. The analyzer simply takes the vibration waveform, whether it is simple or complex, and converts it to a graphic plot or display showing each vibration frequency present along with the amplitude of each frequency. The horizontal axis of the plot is scaled in frequency while the vertical axis is scaled in amplitude (displacement, velocity or acceleration). A vibration spectrum or FFT makes it considerably easier to identify the machine's vibration characteristics compared to trying to convert a time waveform to amplitude and frequency data. More detailed information on vibration frequency analyzers, how they work and their setup and operation is presented in Chapter 3.

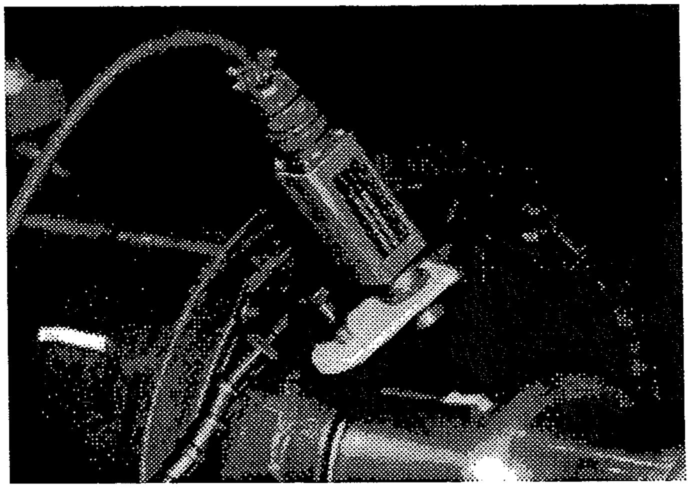


Figure 2-40. Photoelectric reference pickup (photocell) in position for taking digital phase measurements.

Regardless of how phase measurements are taken—with a stroboscopic (strobe) light or digitally with a photocell or lazer-tach, the applications for vibration analysis and balancing are the same. These applications for phase will be covered in much greater detail in the Vibration Analysis and Dynamic Balancing sections of this manual (Chapters 4 and 5).

REFERENCES

1. Rathbone, T. C.; "Vibration Tolerances", Power Plant Engineering, November, 1939.
2. Berry, James E.; Technical Associates of Charlotte, Inc.; Charlotte, NC.; "Vibration Signature Analysis I, Copyright 1993.
3. International Standards Organization, ISO Standard 2372, "Mechanical Vibrations Of Machines With Operating Speeds From 10 to 200 Rev/Sec—Basis For Specifying Evaluation Standards", 1974.
4. International Standards Organization, ISO Standard 2954, "Requirements For Instruments For Measuring Machinery Vibration", 1974.

CRITERIA FOR OVERALL CONDITION RATING (PEAK OVERALL VELOCITY. IN/SEC)

1. Assuming Machine Speed - 600 to 60,000 RPM.
2. Assuming Measurements by Accelerometer or Velocity Pickup as Close as Possilble to Bearing Housing.
3. Assuming Machine Not Mounted on Vibration Isolators (for Isolated Machinery - Set Alarm 30% - 50% Higher).
4. Set Motor Alarm Same as that for the Particular Machine Type unless Otherwise Noted.
5 Set Alarms on Individual External Gearbox 25% Higher than that for a particular Machine Type.

MACHINE TYPE	GOOD	FAIR	ALARM 1	ALARM 2
COOLING TOWER DRIVES				
Long Hollow Drive Shaft	0 - .375	.375 - .600	.600	.900
Close Coupled Belt Drive	0 - .275	.275 - .425	.425	.650
Close Coupled Direct Drive	0 - .200	.200 - .300	.300	.450
COMPRESSORS				
Reciprocating	0 - .325	.325 - .500	.500	.750
Rotary Screw	0 - .275	.275 - .425	.425	.650
Centrifugal With or W/O External Gearbox	0 - .200	.200 - .300	.300	.450
Centrifugal - Integral Gear (Axial Meas.)	0 - .200	.200 - .300	.300	.450
Centrifugal - Integral Gear (Radial Meas.)	0 - .150	.150 - .250	.250	.375
BLOWERS (FANS)				
Lobe-Type Rotary	0 - .300	.300 - .450	.450	.675
Belt-Driven Blowers	0 - .275	.275 - .425	.425	.650
General Direct Drive Fans (with Coupling)	0 - .250	.250 - .375	.375	.550
Primary Air Fans	0 - .250	.250 - .375	.375	.550
Large Forced Draft Fans	0 - .200	.200 - .300	.300	.450
Large Induced Draft Fans	0 - .175	.175 - .275	.275	.400
Shaft-Mounted Integral Fan (Extended Motor Shaft)	0 - .175	.175 - .275	.275	.400
Vane-Axial Fans	0 - .150	.150 - .250	.250	.375
MOTOR/GENERATOR SETS				
Belt-Driven	0 - .275	.275 - .425	.425	.675
Direct Coupled	0 - .200	.200 - .300	.300	.450
CHILLERS				
Reciprocating	0 - .250	.250 - .400	.400	.600
Centrifugal (Open-Air) - Motor & Comp. Separate	0 - .200	.200 - .300	.300	.450
Centrifugal (Hermetic) - Motor & Impellers Inside	0 - .150	.150 - .225	.225	.350
LARGE TURBINE/GENERATORS				
3600 RPM Turbine/Generators	0 - .175	.175 - .275	.275	.400
1800 RPM Turbine/Generators	0 - .150	.150 - .225	.225	.350
CENTRIFUGAL PUMPS				
Vertical Pumps (12' - 20' Height)	0 - .375	.375 - .600	.600	.900
Vertical Pumps (8' - 12' Height)	0 - .325	.325 - .500	.500	.750
Vertical Pumps (5' - 8' Height)	0 - .250	.250 - .400	.400	.600
Vertical Pumps (0' - 5' Height)	0 - .200	.200 - .300	.300	.450
General Purpose Horizontal Pump (Direct Coupled)	0 - .200	.200 - .300	.300	.450
Boiler Feed Pumps	0 - .200	.200 - .300	.300	.450
Hydraulic Pumps	0 - .125	.125 - .200	.200	.300
MACHINE TOOLS				
Motor	0 - .100	.100 - .175	.175	.250
Gearbox Input	0 - .150	.150 - .225	.225	.350
Gearbox Output	0 - .100	.100 - .175	.175	.250
Spindles: a. Roughing Operations	0 - .075	.075 - .125	.125	.175
b. Machine Finishing	0 - .050	.050 - .075	.075	.115
c. Critical Finishing	0 - .030	.030 - .050	.050	.075

CRITERIA FOR OVERALL CONDITION RATING (PEAK OVERALL VELOCITY, IN/SEC)