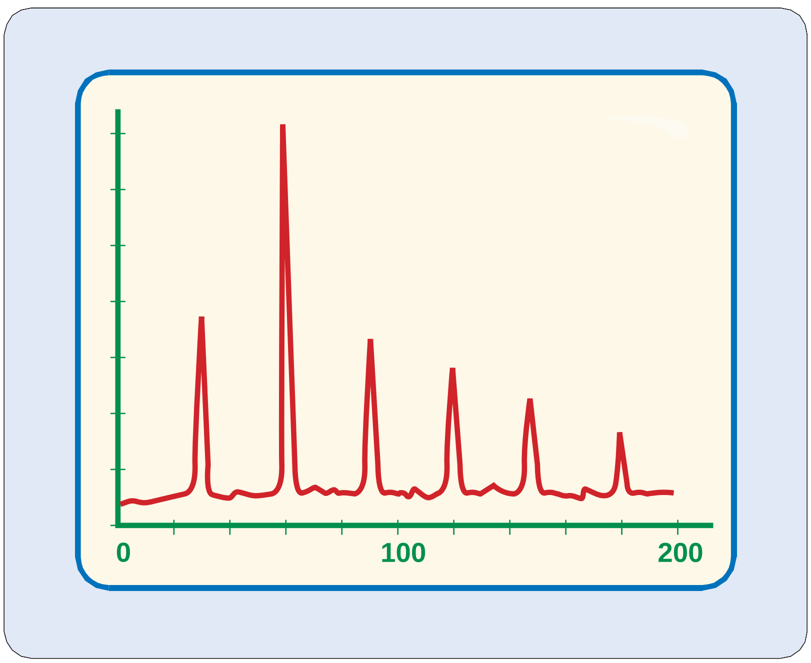
Training Module

Perform Vibration Analysis



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- Training Module and Self-Check
- Knowledge Check and Answer Key
- Blank Answer Sheet
- Performance Check
- Job Aid

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Contents

Contents (continued)

Prerequisite—Describe Basic Vibration Concepts

Training Objectives

Upon completion of this training kit, you will be able to:

- Describe the purpose and importance of vibration analysis
- Describe the various roles in vibration analysis
- Identify sources of vibration in rotating equipment
- Describe vibration severity
- Obtain data on rotating equipment vibration
- Interpret vibration analysis data
- Identify solutions to vibration problems
- Identify the determining factors for selecting the best course of action to correct the vibration problems

NOTE

This training kit may contain technical terms which are new to you. Refer to the glossary, located at the end of this module, for an explanation of terms.

1 Introduction

An effective maintenance program contributes to efficient equipment operation, minimal production and maintenance losses, and extended equipment life. As part of a maintenance program, equipment vibration can be analyzed to determine the equipment's operating condition and to predict when the equipment may fail. The extent of the vibration analysis depends on the purpose for carrying out the analysis:

- identifying changes in equipment condition
- identifying the source and severity of vibration
- predicting when equipment may fail
- determining the best course of action to correct vibration problems

Maintenance personnel must obtain accurate, valid, and reliable vibration data to be able to make effective decisions for correcting vibration problems. The training kit *Describe Basic Vibration Concepts* describes vibration characteristics, three common sources of vibration, and vibration instruments. This module describes additional vibration sources and their associated vibration characteristics and describes:

- the data collection process
- the vibration analysis process

- the standards for assessing vibration severity
- the decision-making process for determining the best course of action to correct vibration problems

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NOTE

The type and availability of vibration instruments varies from site-to-site. If you **cannot** effectively operate the vibration instrument(s) available on site, you should:

- obtain on-site coaching to use the vibration instrument(s) to take vibration readings
- thoroughly review literature (vibration instrument manuals, user guides, etc.) provided by the vibration instrument manufacturer

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2 Sources of Vibration

The three most common sources of vibration are imbalance, misalignment, and resonance. Some vibration analysts estimate that over 90% of all vibration problems may be due to these sources in the following proportions:

- 40% imbalance
- 30% misalignment
- 20% resonance
- 10% others

NOTE

The training kit titled *Describe Basic Vibration Concepts* describes the vibration characteristics of imbalance, misalignment, and resonance.

Vibrations caused by imbalance, misalignment, and resonance may be present at the same time. Generally it is best to eliminate one vibration source at a time, starting with resonance. Resonance can be reduced by bracing the equipment and piping. In some cases, bracing the piping at one location causes the resonance to occur at a different location. The rule of thumb is to use bracing for piping and structures which have a cross section of less that 20 cm (8 in.) because the vibrational energy is small. For resonant parts with a cross section greater than 20 cm, the vibrational energy is large—bracing will probably result in the vibration being transferred to some other location. Resonance can also be reduced by changing the frequency of the forced vibration. A small change in the equipment's rpm may significantly reduce the severity of the resonant vibration. Changing the load on the equipment also reduces the forced vibration energy.

After the resonant vibration is under control, correct the misalignment next since it usually takes less work to correct misalignment than to correct imbalance. After vibrations due to resonance and misalignment have been minimized, vibration due to imbalance may be tolerable.

NOTE

All phase descriptions in this training kit and in the training kit *Describe Basic Vibration Concepts* are based on observations of the phase behavior generated by a strobe light connected to the vibration instrument and triggered by the machine's vibration.

2.1 Roller Bearing Vibration

The technology to produce precision bearings is very advanced—bearings leaving the manufacturer are of high quality. As a rule, bearing failures due to manufacturing defects are low. Most bearing failures are caused by service conditions in which the bearings operate. The main service conditions which contribute to bearing failure include:

- contamination, including moisture
- lack of lubrication
- over stress
- damage created after manufacturing (caused during transportation or as a result of poor installation practices)

Vibration analysis is very reliable in identifying bearing defects. However, analyzing bearing vibration is difficult because of the multiple frequencies generated by bearings. All bearings produce four types of vibration:

- fundamental train frequency
- ball spin frequency
- outer race frequency
- inner race frequency

The formulas for calculating the vibration frequencies are complex. For simplicity, an approximation of the frequencies can be calculated by using the following formulas:

Fundamental train frequency = 0.4 x rps
Outer race frequency = 0.4 x rps x N
Inner race frequency = 0.6 x rps x N

rps = revolutions per second
N = number of bearing roller elements/balls

Example:
rps = 20 Hz
N = 10 balls

Fundamental train frequency = 0.4 x 20 Hz = 8 Hz
Outer race frequency = 0.4 x 20 Hz x 10 = 80 Hz
Inner race frequency = 0.6 x 20 Hz x 10 = 120 Hz

Generally, bearing defects first start with the outer race. Each time a roller element encounters a defect on the race, metal-to-metal contact is made. The metal-to-metal impacts can result from high loads, lack of lubrication, or a bearing defect. Each time metal-to-metal contact is made, a shock pulse is created. Since most bearings have 10 to 15 roller elements, the period between shock pulses is between 4 to 10 times running speed (calculated using the above formulas). The metal-to-metal impacts show up as shock pulses at frequencies between 1000 Hz and 10 000 Hz. As the bearing continues to wear, the inner race begins to produce lower frequency shock pulses—a sign that the bearing is leading to failure.

Because the bearing vibrations are at a high frequency, an accelerometer must be used to measure the vibrations. The shock pulses from bearing vibrations may not show up distinctly on an analyzer when viewing the bearing vibrations over a broad frequency range. By selecting the bearing's frequency and viewing the vibration over a period of time, the analyzer may show the shock pulses more distinctly.

Take the vibration readings close to the bearing. Vibrations from bearings tend to be localized and not transmitted to other parts of the equipment. To discriminate between bearing vibrations and other vibrations, take vibrations readings at several locations on the equipment. Vibrations common to several locations can often be eliminated as originating from a bearing.

Figure 1— Example 1: Low Bearing Vibration (Time)

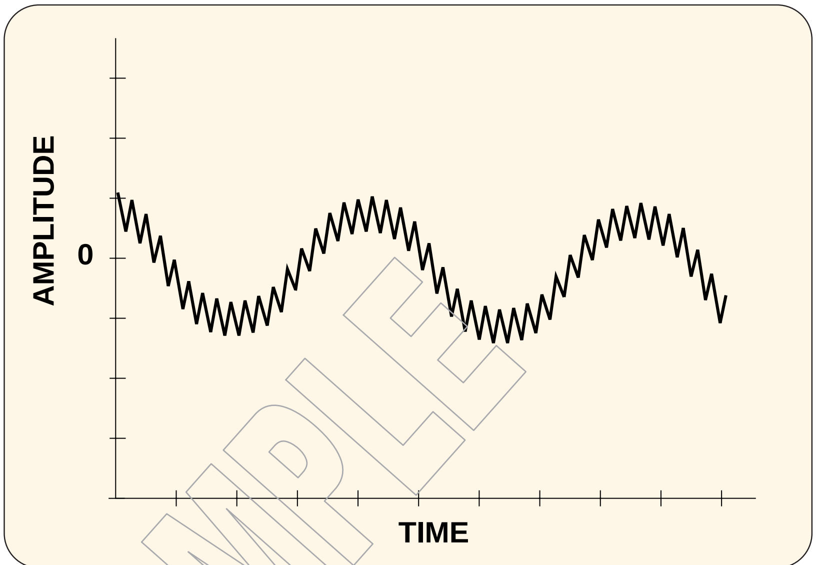
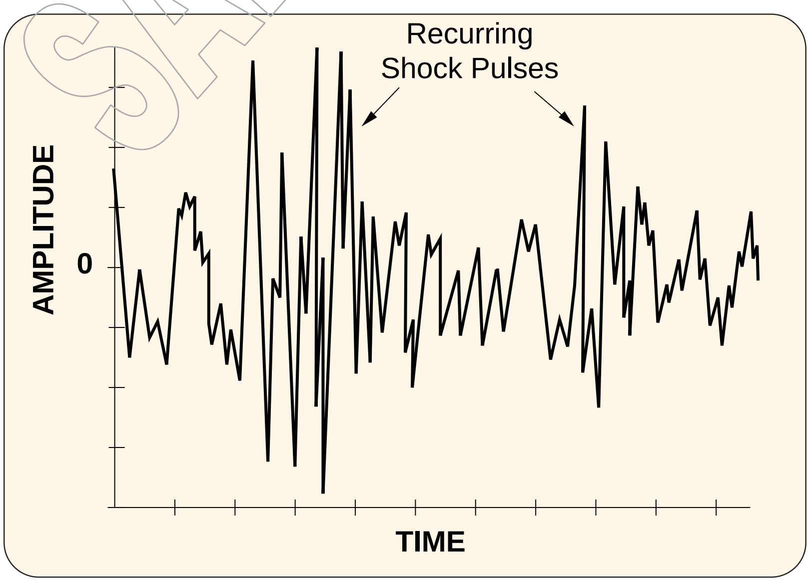


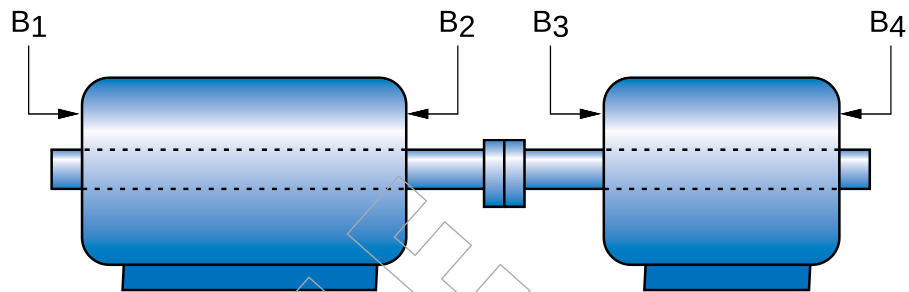
Figure 2— Example 2: High Bearing Vibration (Time)



Misaligned bearings produce vibrations that have the same harmonics as the vibrations produced by shaft misalignment or by a bent shaft. To determine if the source of vibration is due to bearing misalignment or other sources, follow these troubleshooting procedures:

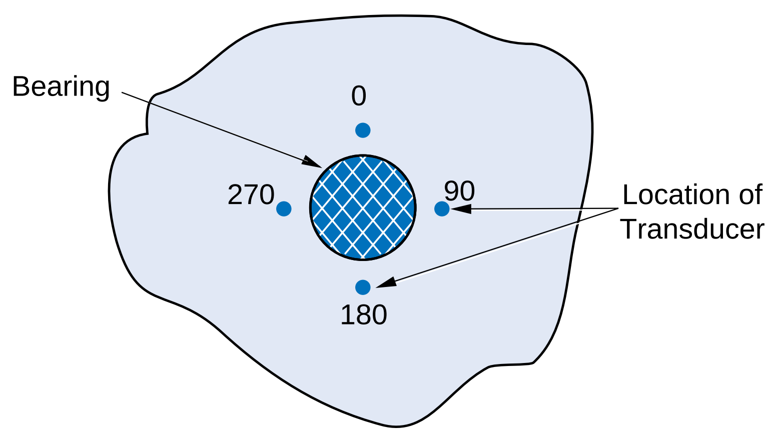
- Take *axial* phase angle measurements at all four bearings (see Figure 3).

Figure 3— Location on Equipment for Taking Phase Measurement



- For each bearing, measure the phase angle at 0°, 90°, 180°, and 270° (see Figure 4). If the transducer is moved from one bearing to another, the transducer may have to be turned 180°. When comparing the phase angles between two bearings in which the transducer must be rotated 180° to obtain a reading, the 180° must be either added or subtracted from the phase measurements for one of the bearings to obtain an accurate comparison of phase angles. Referring to Figure 3, no phase angle correction is required when comparing the phase angle measurements between B_1 and B_3 or between B_2 and B_4. However, the 180° correction must be made when comparing the phase angle measurements between B_1 and B_2 or between B_3 and B_4.

Figure 4— Locations at the Bearing for Taking Phase Measurements



- If there is a large shift in the axial phase angle between bearings on the same equipment (e.g., B1 and B2), there is a good possibility that the equipment's shaft is bent near or through the bearing, or the bearing is misaligned.

There is a 180° shift in the phase angle if the two transducers located at the bearings are pointing in opposite directions.)

- If there is a large shift in the phase angles between the inboard bearings on the driver and the driven equipment (e.g., B2 and B3), the vibration is probably due to misalignment or a faulty coupling.
- If all the bearings vibrate in phase, the source of vibration is due to imbalance or a resonating foundation.
- Uncouple the shafts and run the driver. If the problem is shaft misalignment, the vibration should disappear because there is no strain on uncoupled shafts.
- Use a dial indicator to measure shaft runout. Note that this test could also indicate an out-of-round shaft.

If these tests indicate that there is no misalignment and the shafts are not bent, then bearing misalignment is the most likely source of vibration. To verify that the source is bearing misalignment, visually inspect the bearing for wear patterns.

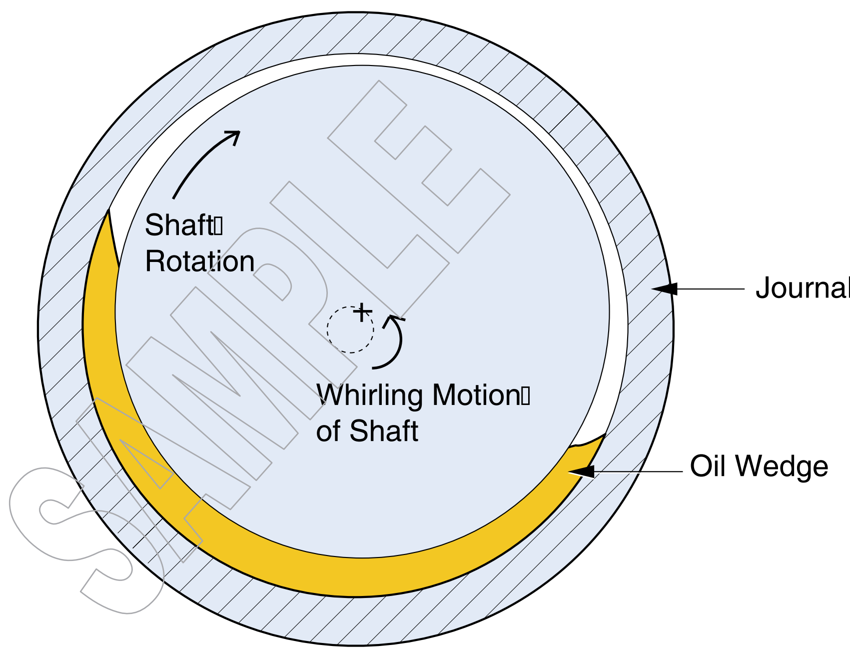
A faulty bearing does not necessarily have to be replaced. A faulty bearing can continue to operate for a long time; it may be possible to continue operating the equipment until the next scheduled maintenance shutdown.

A special bearing failure case involves shafts with two bearings mounted at one end. Sometimes only one bearing fails and the other bearing is in excellent condition. This situation can occur if one bearing's OD (outside diameter) is slightly larger that the other bearing's OD. The larger OD bearing takes all the load, resulting in premature bearing failure. When selecting replacement bearings, matching part numbers does not ensure that the bearing ODs are the same. Before installation, check to ensure the two bearings have matching ODs.

2.2 Oil Whirl

Oil whirl is a condition specific to machines that have pressure lubrication of sleeve bearing (e.g. journals). Oil whirl is most likely to occur when a machine has a light load and operates at a relatively high speed. During operation, the shaft rides on a wedge of oil located between the shaft and the journal. If the shaft experiences a shock caused by a load change, the oil wedge experiences an additional load. The oil wedge then forces the shaft to revolve around the journal in the opposite direction to the shaft's rotation (refer to Figure 5).

Figure 5—
Oil Whirl

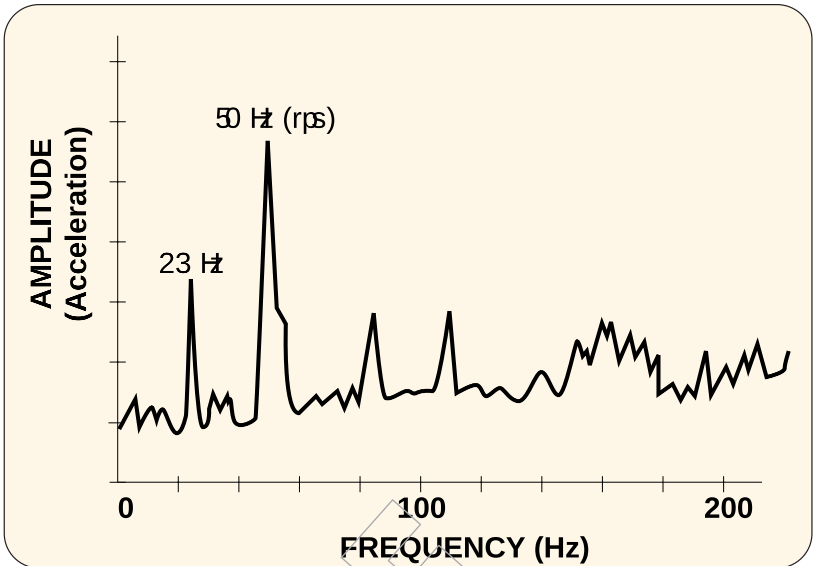


Oil whirl produces a vibration frequency which is always *less* than one-half the rotational speed of the shaft. As a general rule, the oil whirl vibration frequency will fall between 45% and 48% of the rotational frequency.

Temporary solutions for reducing oil whirl include:

- changing the oil's viscosity
- changing the oil's temperature
- using a different oil
- increasing the load on the equipment

Figure 6— Oil Whirl Vibration (Frequency)



The long-term solution for eliminating oil whirl is to reduce the clearance of the journals.

2.3 Looseness

Equipment looseness vibration is characterized by the generation of harmonics. Harmonics are generated because the loose part is not allowed to complete its natural full motion. A physical object such as a hold-down bolt causes the loose part to come to a sudden stop. When the loose part hits the restricting object, some of the kinetic energy is released in the form of harmonic vibrations. Often the 2 x running speed harmonic is the most dominant frequency (largest amplitude). In cases of moderate looseness, 1 x the running speed harmonic frequencies are generated. In cases where looseness is extreme, 1/2 x the running speed harmonic frequencies are generated (see Figures 7 and 8). Care must be taken not to mistake a 1/2 x the running speed vibration created by looseness, with the slightly less than 1/2 x running speed vibration created by oil whirl. Phase readings for mechanical looseness will show a difference in phase between the rotating equipment and the equipment's base.

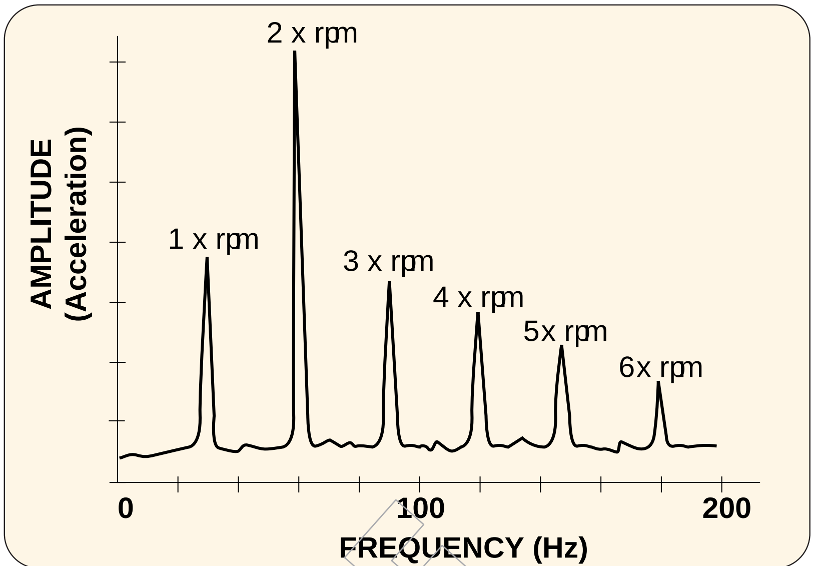


Figure 7— Example 1: Less Severe Looseness Vibration (Frequency)

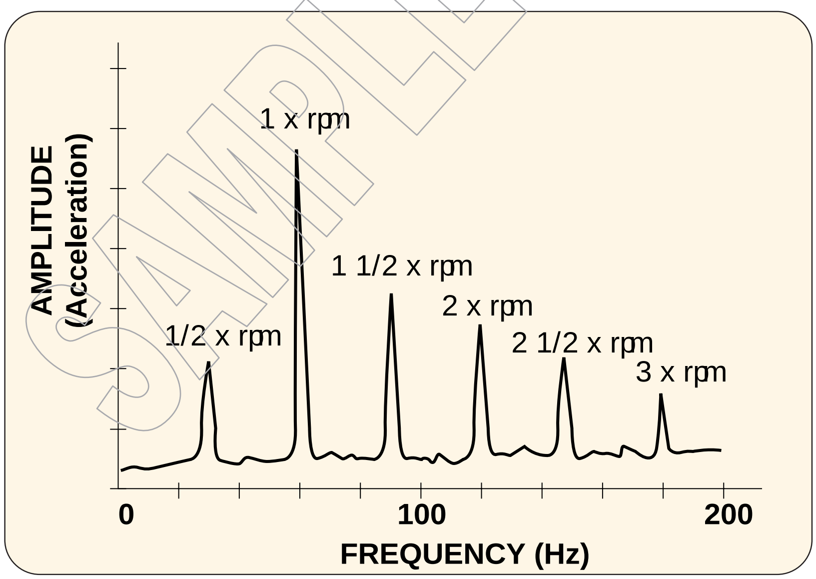


Figure 8— Example 2: Extreme Looseness Vibration (Frequency)

In some cases, correcting the symptom (i.e., the looseness) solves the vibration problem. If the equipment vibration level is still considered severe after tightening the loose parts, the source of the vibration must be identified and corrected.

2.4 Drive Belt and Pulley Vibration

Pulleys and belts are treated together because the relative movement between pulleys and belts sets up vibrations in each other.

Drive belts and pulleys can vibrate because of:

- belt damage
- pulley eccentricity
- pulley wobble
- pulley imbalance
- forced vibration from external sources

Belt defects include uneven belt width, a bump at a seam, cracks, and missing material. Each time a belt defect passes over a pulley, the defect creates a vibration pulse. The vibration pulse shows up at the belt's speed and its harmonics. Significant harmonics at 2 x belt rpm may be created. If there are more than two pulleys, the vibration pulse may show up at harmonics greater than 2 x belt rpm.

Belt speed (in rpm) can be determined either by using a strobe light or by calculating the speed mathematically. To use a strobe light to determine belt speed:

- shut down the machine
- place a chalk mark on the belt
- start the machine
- starting at a low frequency, adjust the strobe light frequency until the chalk mark remains stationary

To mathematically calculate belt speed, the following information must be known:

- a pulley's pitch diameter (D)
- a pulley's rpm
- belt length (L)
- $\pi = 3.14$

$$\text{Belt speed}_{\text{(rpm)}} = \frac{\pi \times D_{\text{(pulley)}} \times \text{rpm}_{\text{(pulley)}}}{L_{\text{(belt)}}} = \frac{\pi \times D \times \text{rpm}}{L}$$

To identify belt defects, take two sets of radial vibration readings on the bearing housing: one set of readings taken parallel to the belt tension, and the other set of readings taken perpendicular to the belt tension. Generally, belt defects create the highest vibration amplitudes in the direction parallel to the belt tension. Figure 9 shows vibrations from a defective belt. The drive pulley operates at 32 Hz (1920 rpm); the driven pulley operates at

20 Hz (1200 rpm). In this example, the belt speed is 15 Hz (900 rpm). Figure 10 shows the vibration after the defective belt was replaced.

Figure 9— Vibration Caused by a Defective Belt

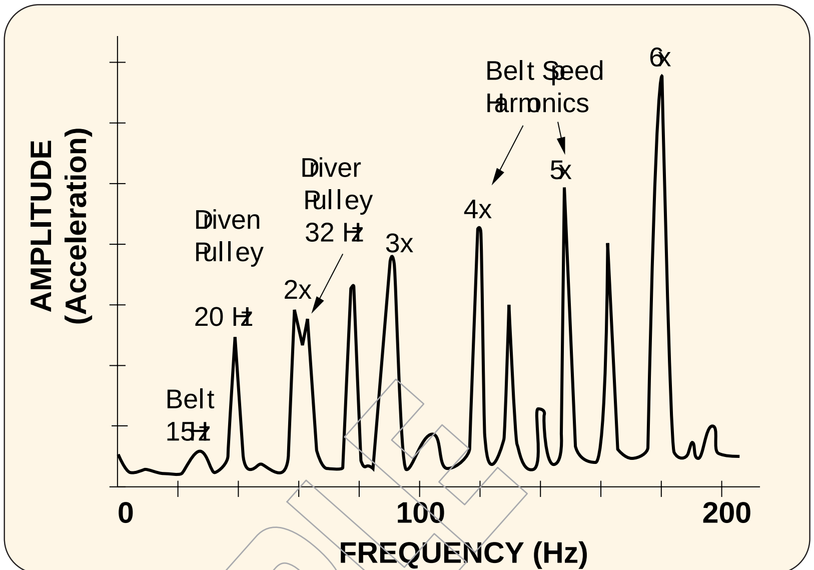
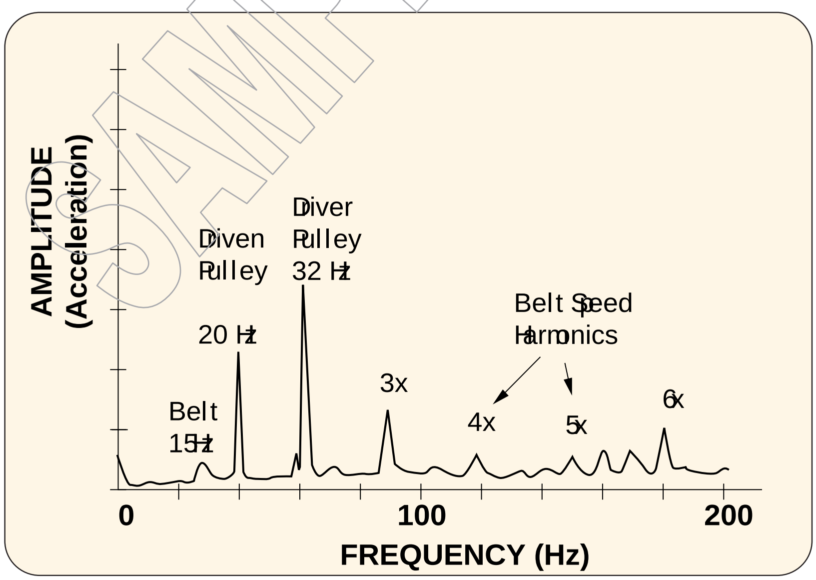
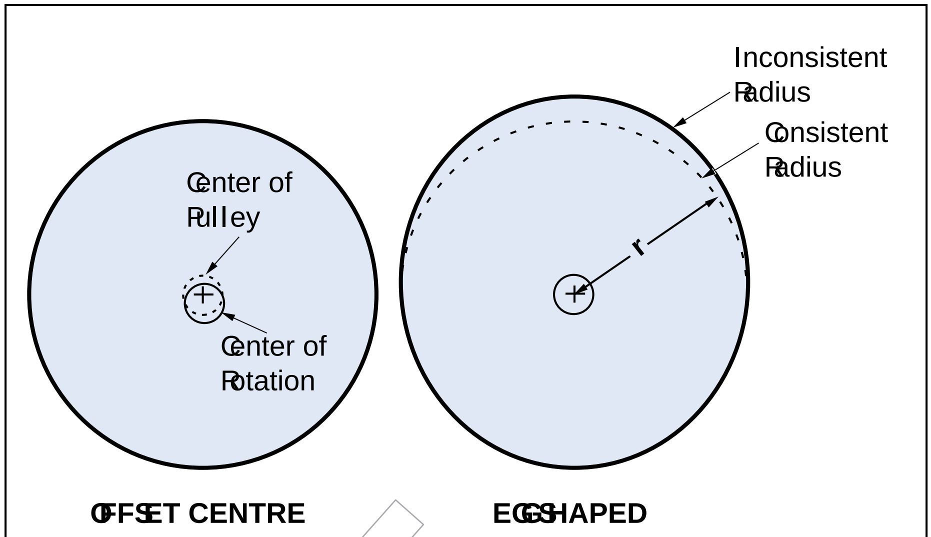


Figure 10— Vibration Caused by a Good Belt



Pulley eccentricity, wobble, or imbalance can cause excessive vibrations. A pulley is eccentric when its radius is not consistent. Pulley eccentricity is caused when the pulley is out-of-round (egg shaped), or has an offset shaft center. Eccentricity can also cause imbalance. Unfortunately, correcting an eccentric pulley's imbalance does not eliminate the vibration.

Figure 11—
Eccentric Pulleys

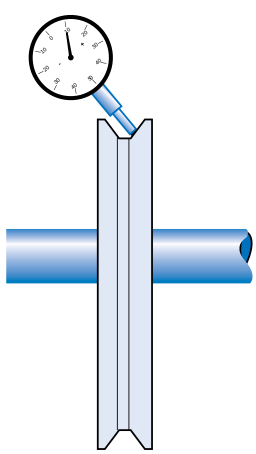


A pulley wobbles from side to side when it does not run true to the plane of rotation. The wobble in pulleys that have inside bushings can sometimes be corrected by adjusting the bushing bolts. If a wobbling pulley does not have a bushing, the pulley must either be machined or replaced.

To check for eccentricity and wobble:

- Place a dial indicator perpendicular to the belt's running surface. The belt usually does not have to be removed to complete this check.
- Slowly turn the pulley by hand and observe the amount of runout.

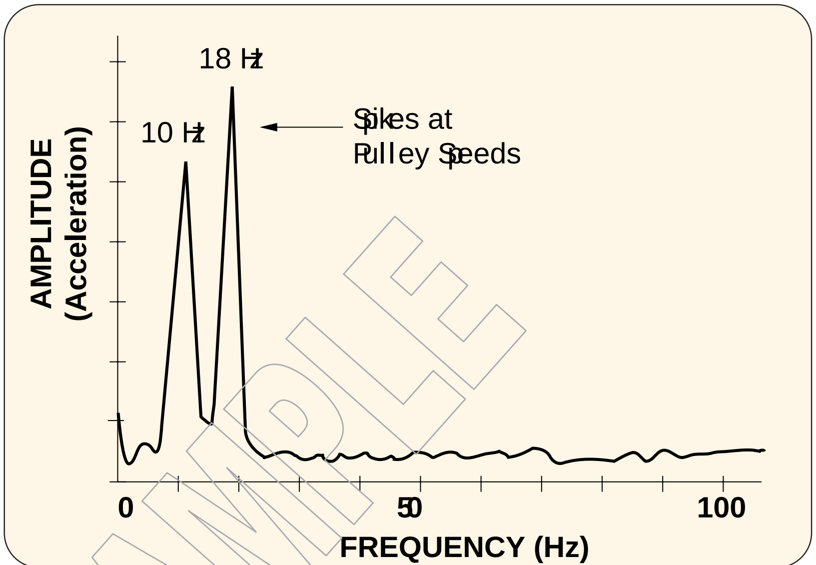
Figure 12—
Using a Dial Indicator to Check Pulleys



A good pulley has a TIR (Total Indicator Reading) of less than 0.05 mm (0.002 in.). A pulley with a TIR greater than 0.125 mm (0.005 in.) should be either corrected or replaced to minimize vibration problems.

An eccentric pulley momentarily stretches the belt. The belt then vibrates in the radial direction. A wobbling pulley causes the same effect on a belt as an eccentric pulley, except that the belt vibrates in the axial direction. Pulleys that are eccentric, imbalanced, or wobble, produce the same vibration characteristics: excessive vibration at the pulley's running speed (see Figure 13).

Figure 13— Belt Vibration Caused by a Defective Pulley



Vibrations from surrounding equipment can also cause belts to vibrate excessively. If the frequency of vibration from surrounding equipment is close to or a harmonic of a belt's natural frequency, the belt will resonate. To determine if the source of vibration is from the belts and pulleys or from external equipment, use the following steps:

- Use a strobe light to determine the frequency of belt vibration. Note that the sections of belts between pulleys may have vibration frequencies different from each other due to varying belt length (multiple pulleys) and varying tension (tension side and slack side).
- Use a vibration instrument to check the frequency of the surrounding equipment.

If the frequency of surrounding equipment is at the belt's natural vibration frequency or at a harmonic of the belt's natural vibration frequency, the source of vibration is probably external. Two methods can be used to reduce belt vibration caused by external forced vibrations:

- Change the forced vibration frequency of the surrounding equipment.
- Change the belt's tension to change the natural vibration frequency of the belt. Note that there may be little adjustment available between the belt being too loose and too tight.

Use the following steps to adjust the tension on the belt to obtain the minimum belt vibration:

- Connect a vibration analyzer to the pulley's bearing. The transducer should be oriented in the direction which has the greatest vibration amplitude.
- While the machine is operating, adjust the belt tension to obtain the minimum vibration as indicated on the vibration analyzer.

Usually it is more cost-effective to first deal with belt and pulley defects before resorting to balancing pulleys. The checklist at the end of this training kit provides a general strategy for dealing with pulley and belt vibration problems.

On multiple belt drives, belts must have the same relative slippage to minimize vibration. If one or more belts slip at different rates, the belts eventually line up at an unfavorable location, such as at the belt seams. As the seams pass in unison around the drive pulley, extra tension is put on the motor. At other times the belts may line up in such a manner that the vibrations are subtracted. The net result of uneven belt slippage is that over a long period of time, one or more belts slowly build up to a resonance and then slowly die down. The cycle time for the resonance to occur could vary, say from one-half minute to several minutes, depending on the degree of uneven belt slippage.

To check for uneven belt slippage, stop the machine and place a chalk mark across all the belts. Start the machine and use a strobe light to observe the chalk marks. If the marks begin to move relative to each other, the belts are experiencing uneven slippage.

When replacing belts on multiple belt drives, order the replacement belts as a *matched* set. Belts from a matched set are precisely measured to ensure their dimensions are identical. Belts which only have the same part number are not a matched set.

2.5 Gear Vibration

Generally, gears are designed to last the lifetime of the machine. Premature gear failure is often due to misalignment, imbalance, a bent shaft, or improper lubrication.

Gear teeth in contact must transmit all of the power from the prime mover to the driven equipment. During contact, the gear teeth undergo major changes in force. The contact teeth deflect under load and then rebound as the contact is broken. Over the lifetime of the gear, the teeth wear and can develop cracks due to fatigue.

A single tooth may become defective due to wear, deformity, chipping, or breakage. A deformed tooth will generate a vibration pulse at running speed. Unfortunately, a faulty bearing and misalignment also cause vibrations at running speed. Two indicators differentiate vibration caused by a defective tooth from vibration caused by a defective bearing or by misalignment:

- Bearing vibration can only be detected in the vicinity of the bearing, whereas gear tooth vibration can be detected at more than one location.
- Alignment vibration occurs in both the radial and axial orientations, whereas a defective tooth vibration occurs primarily in the *radial* orientation.

A gear generates a vibration at the gear mesh frequency. The gear mesh frequency is equal to the number of gear teeth times the shaft's rotational speed.

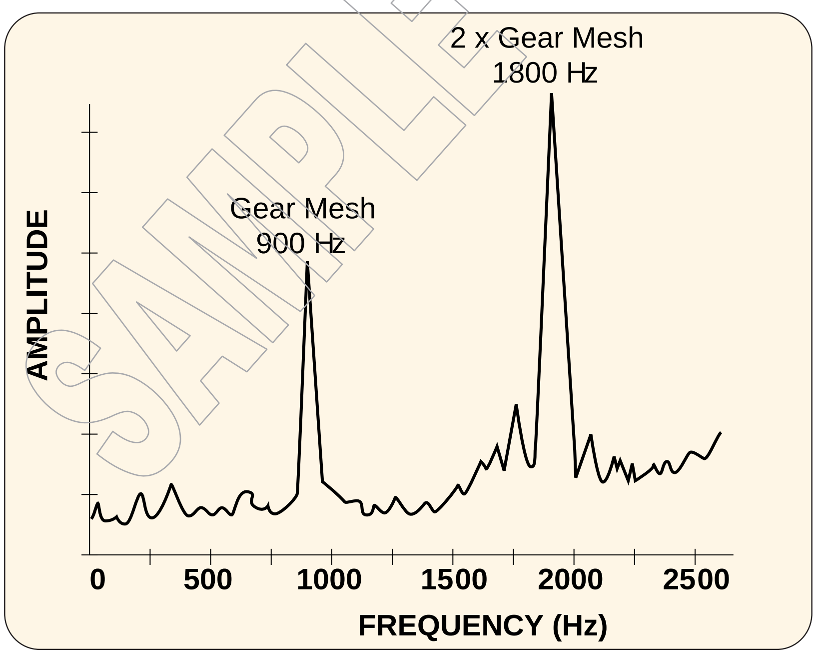
Gear mesh frequency = number of teeth x rps

Gear problems will show up at the gear mesh frequency, and at twice the gear mesh frequency. Figure 14 shows the vibration pattern of a gear with 36 teeth operating at 25 Hz (1500 rpm).

Gear mesh frequency	=	number of teeth x rps
Gear mesh frequency	=	36 x 25 Hz
Gear mesh frequency	=	900 Hz
2 x gear mesh frequency	=	1800 Hz

The gear mesh frequency of two meshed gears is the same for both gears. The high speed gear operates at a higher speed but has proportionally fewer teeth than the lower speed gear. Over a specified period of time, the total number of teeth from each gear making contact with each other is the same.

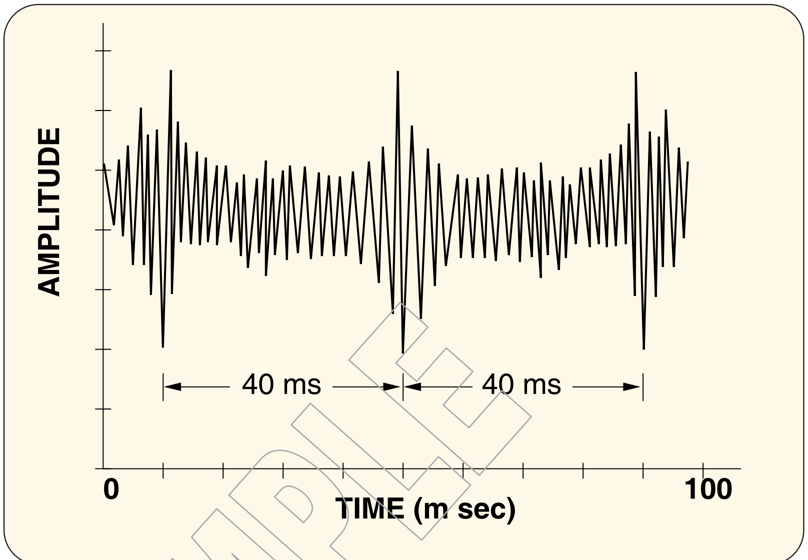
Figure 14— Vibration Caused by a Defective Gear (Frequency)



Often the 2 x gear mesh frequency is more dominant that the 1 x gear mesh frequency and is a good indicator that a gear problem is developing. Because gear mesh vibration frequencies are high, an accelerometer must be used to obtain accurate measurements.

Further diagnosis of a gear can be carried out by selecting the gear mesh frequency (or 2 x the gear mesh frequency) and observing the vibration over time. In Figure 15, the single defective tooth generates a spike once per gear revolution (40 ms–milliseconds). A millisecond is 1/1000 of a second.

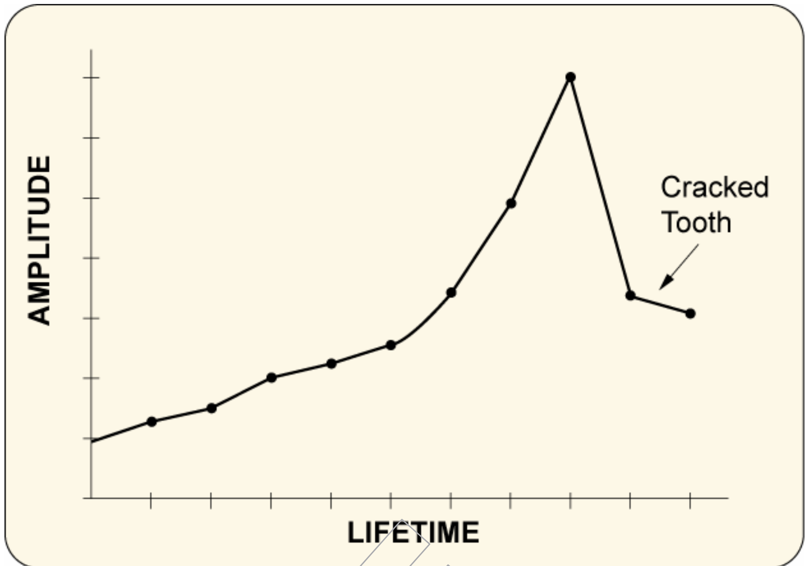
Figure 15— Vibration Caused by a Defective Gear (Time)



At low loads, gears can experience backlash. Backlash occurs when the force of the load transfers back and forth between the two mating gears. Backlash vibrations are inconsistent in amplitude. Generally, gear vibration amplitude varies with the load on the gears. To obtain accurate gear vibration data over a long period of time (trending), vibration measurements must be taken with the equipment operating under the same load conditions.

New gears generate a high frequency vibration which drops off after a few hours of operation. The gear vibration frequency then remains stable over the lifetime of the gears. However, vibration amplitude increases over time; the gears become louder and louder. If the gear vibration amplitude suddenly drops, gear failure is likely to occur. This situation arises due to the physical condition of a gear tooth. During contact, a gear tooth will only flex a small amount. The force of impact produces a vibration of a specific amplitude. If the tooth cracks, the tooth flexes more, absorbing the force of impact. The resulting vibration has a lower amplitude.

Figure 16—
A Lifetime Trend of Gear's Vibration



2.6 Rubbing Vibration

Rubbing is often a symptom of equipment problems such as imbalance or misalignment. The friction between the rubbing parts produces a broadband of high frequencies. Sometimes rubbing will cause vibrations at running speed and at the associated harmonics. However, the vibrations are often symptoms accentuating other vibration problems.

End of Sample

A full licensed copy of this kit includes:
- Training Module and Self-Check
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