Introduction to Vibration Course

Sep 19, 2014

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Introduction

Vibration Course

1. Vibration Analysis content.
2. More Solved Examples.
3. Presenter from Industry working as a vibration analyst.
4. All course materials will be uploaded to
   drahmednagib.com
5. Additional lectures in Matlab
6. Announced office Hours for Professors and teaching assistants

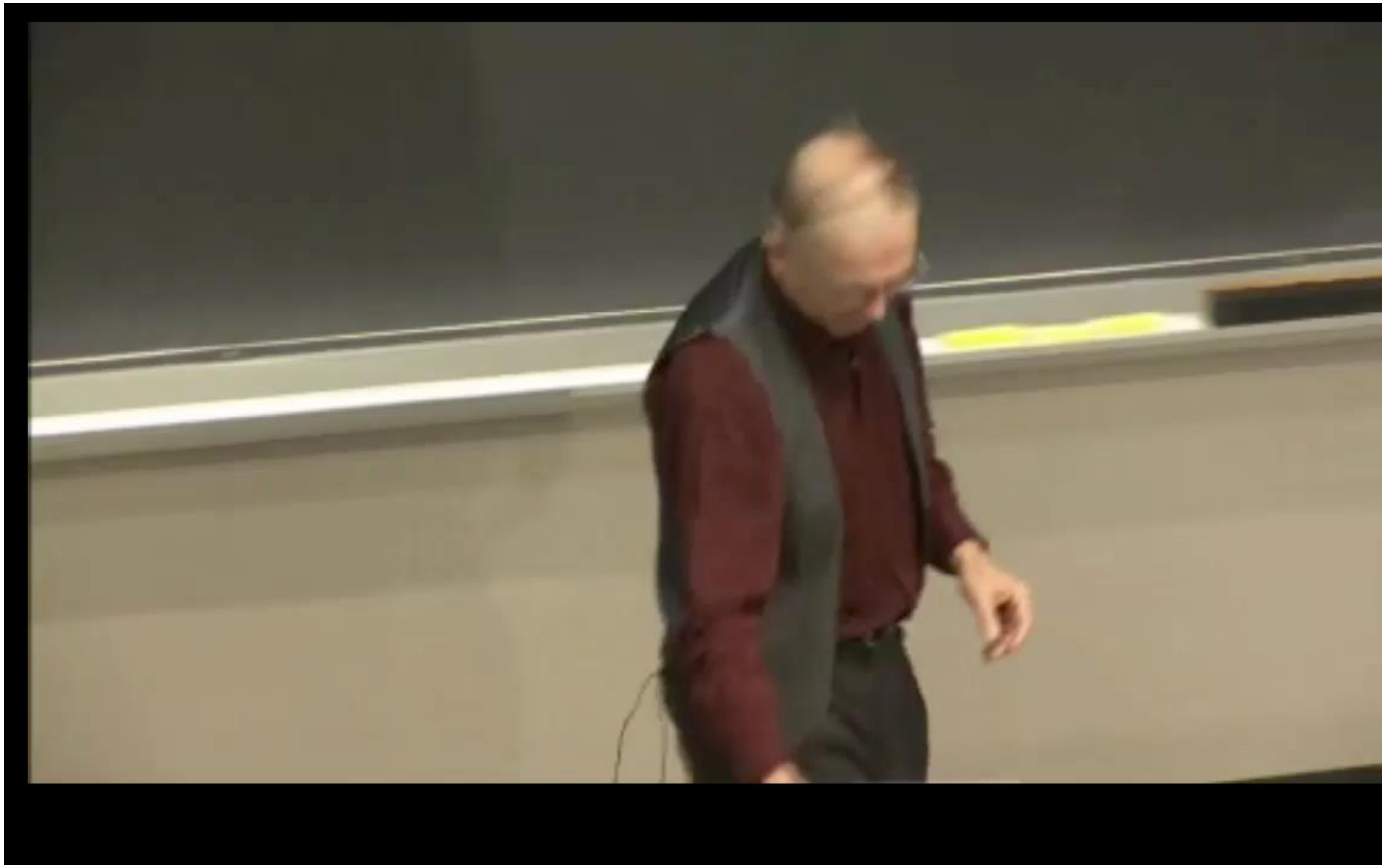
Course Materials

drahmednagib.com

Vibration Terminologies

Vibration Definition

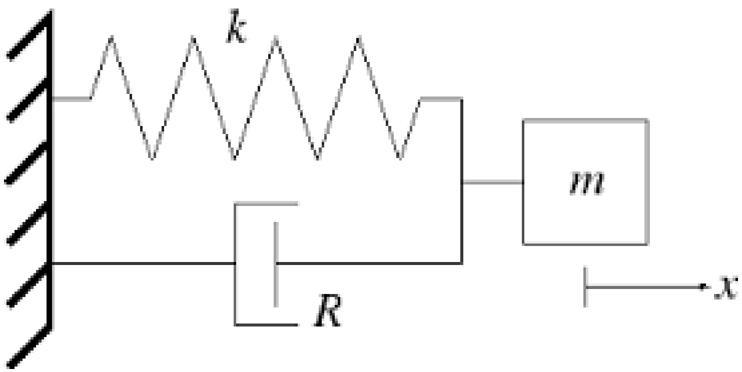
Vibration is the study of the repetitive motion of objects relative to stationary frame of reference or nominal position (usually equilibrium).

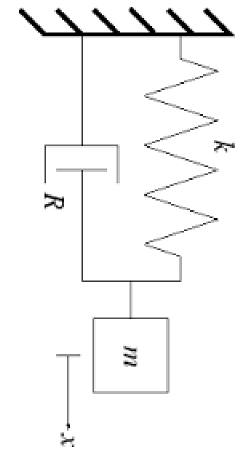


Vibration Definition

Single Degree of freedom system

A system that has one degree of freedom.





The governing equation of single degree of freedom system is

$$m\ddot{x} + c\dot{x} + kx = 0$$

<u>Vibration System properties</u>

1. Mass

$$Inertia\ Force = Mass \times Acceleration$$

Mass = (volume) (density)

Weight = (mass) (g)

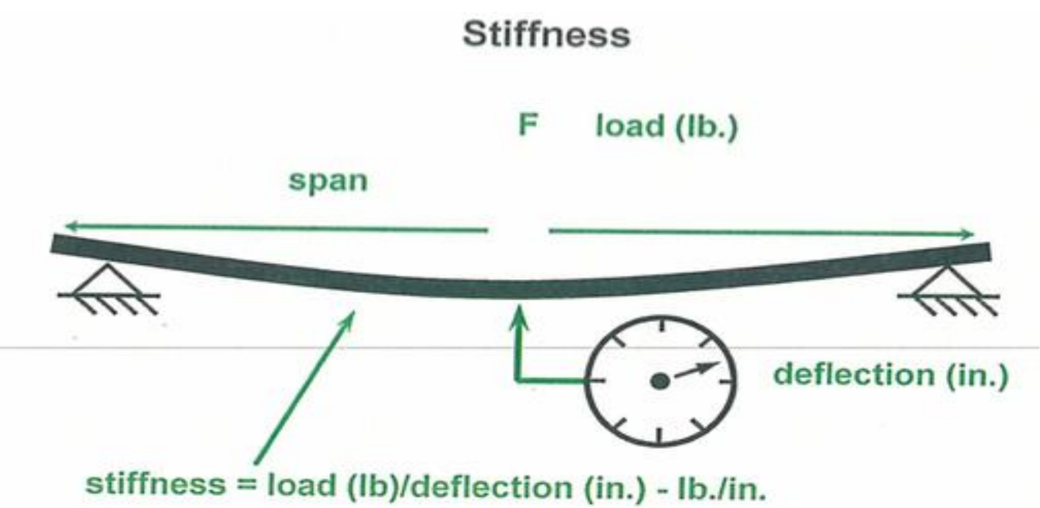
or

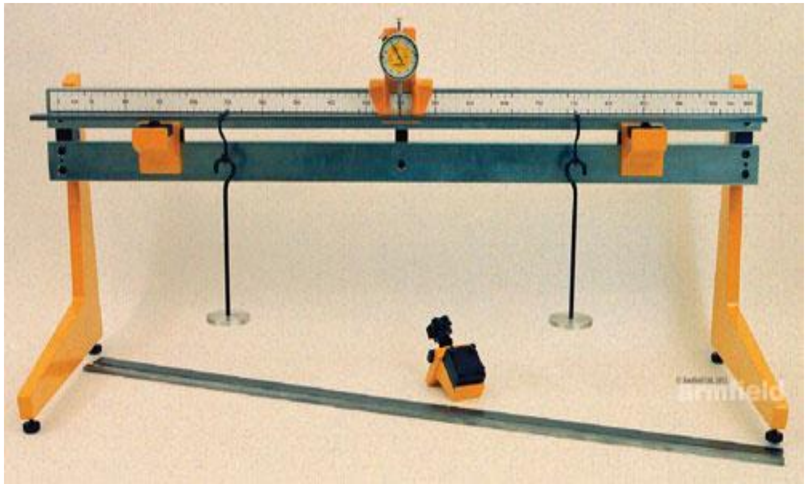
Mass = weight/g

Vibration System properties

2. Stiffness

$$Force = stiffness \times Deflection$$
$$F = k\delta$$
$$k = \frac{F}{\delta}$$

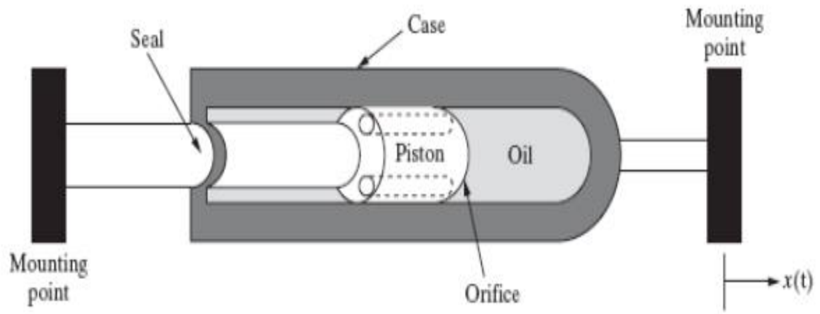




Vibration System properties

3. Viscous Damping

$$Damping\ Force = Coefficient \times Velocity$$



Vibration System properties

3. Viscous Damping

https://www.youtube.com/watch?v=lA30mblo6HQ

Vibration Definition

Natural Frequency

Natural Frequencies are properties of the system and are dependent on its distribution of mass and stiffness. Every system has a number of natural frequencies.

For a a single degree of freedom, undamped system: If the vibration of the system is initiated, the motion will be sustained at the system natural frequency without additional energy input.

Resonance

If a forcing frequencies close to a natural frequency, a resonance exists, and the vibration level is high because the machine absorbs energy easily at its natural frequencies.

Resonance is a dangerous condition in a mechanical or structural system and will produce unwanted large displacements or lead to failure.

Vibration Definition

$$w = 2\pi f = \frac{2\pi}{\tau}$$

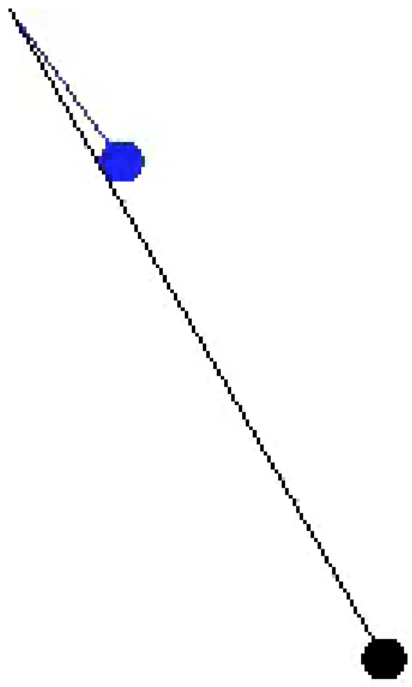
Where

w: circular frequency (rad/sec)

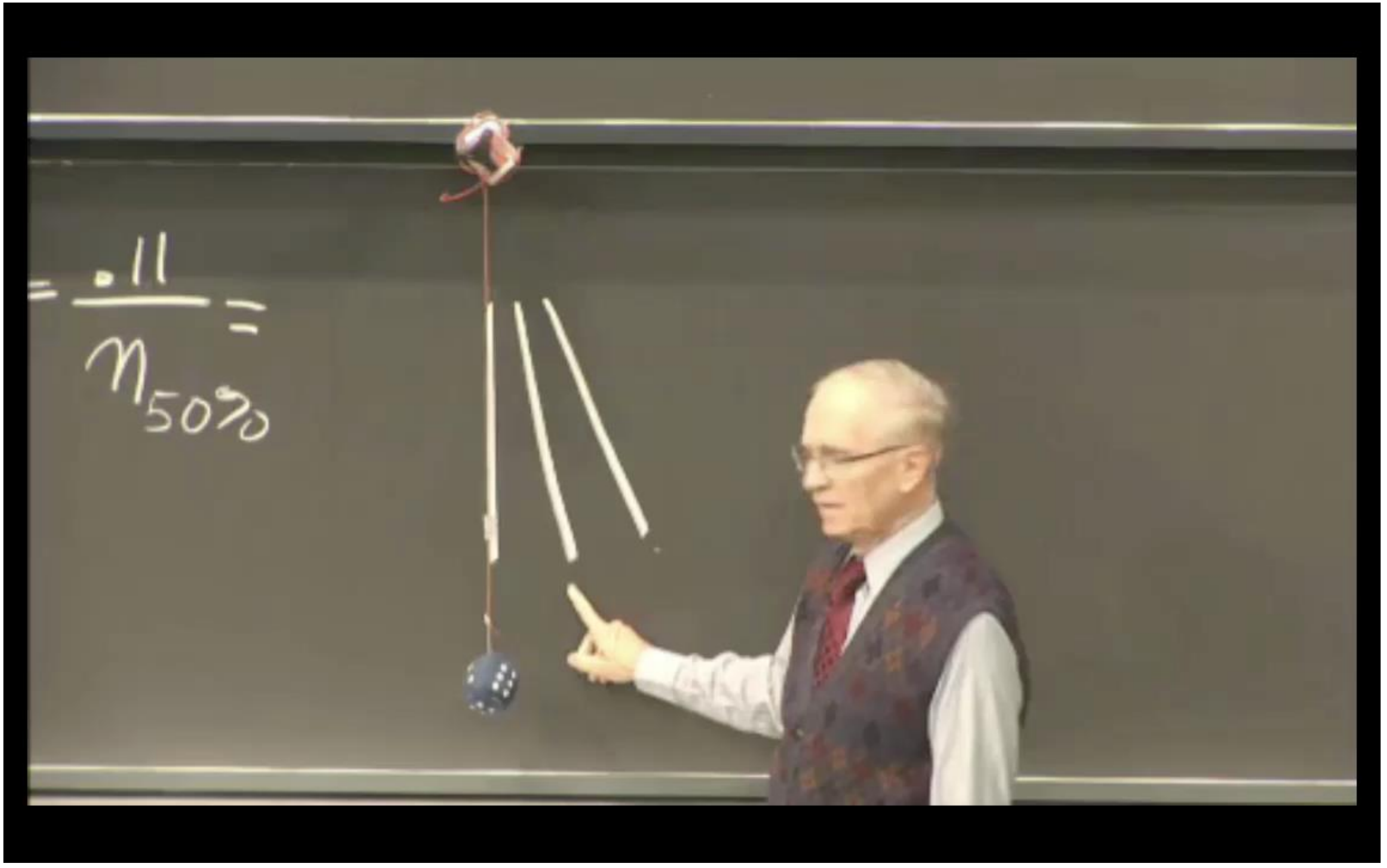
f: frequency

τ: Time of one cycle

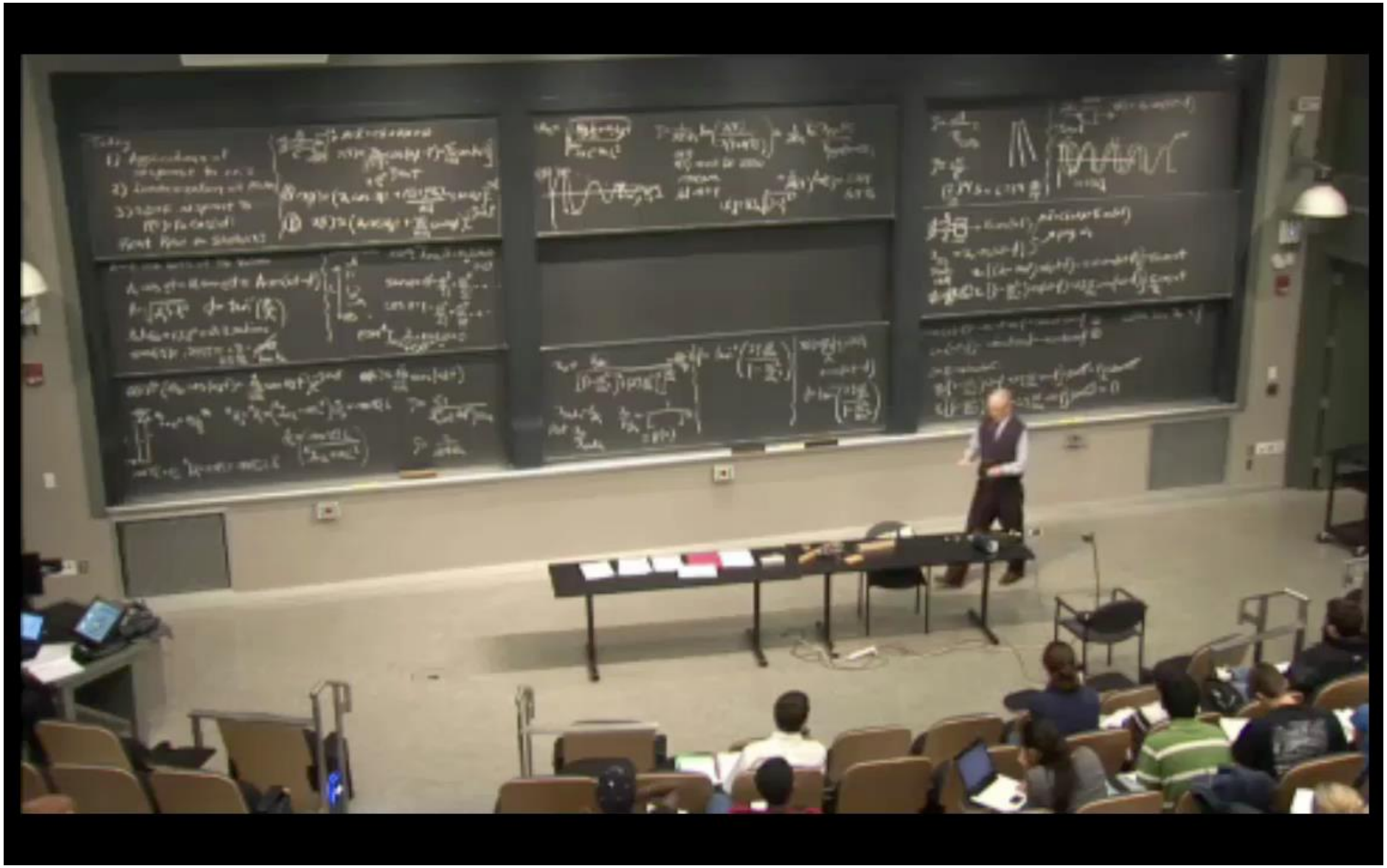
Vibration Definition



Vibration Definition



Vibration Definition



Vibration Real life Examples

The motion of guitar spring
Car Suspension System
Washing Machine
Pump and Turbines
Cell phone vibration.
Screener (vibratory separator).

Resonance Phenomena

Resonance Phenomena

Millennium Bridge – A recent Vibration Problem (2000)

The bridge was opened and closed within 3 days from its opening due to undesirable vibration.

Millennium Bridge – A recent Vibration Problem (2000)

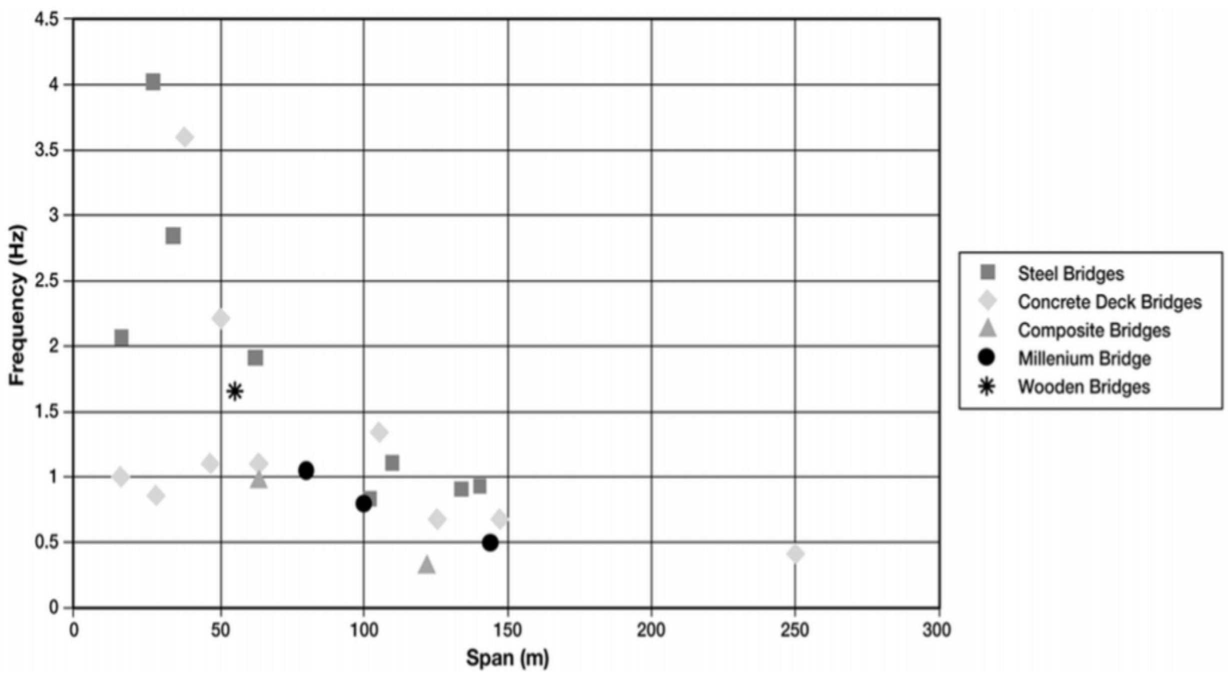
https://www.youtube.com/watch?v=eiaM_LZUsqM

Millennium Bridge – A recent Vibration Problem (2000)

Natural Frequency of bridge in lateral directions are 0.48 Hz, 0.78 Hz, o.95 and 1.05 Hz.
The typical footfall rate for purposeful walking is around 2 steps per second. In large crowds and in the absence of vibrations this rate drops to 1.4 steps per second or lower. This means that the vertical forcing frequency is generally in the region of 1.2–2.2 Hz. Since alternate footsteps apply forces in opposite lateral directions, the predominant lateral forcing frequencies are half of these values, so are in the range of 0.6–1.1 Hz. When locked-in to a lateral vibration mode within this frequency range, the pedestrian footfall rate will tend to be twice the lateral frequency of the bridge, even though this footfall rate may not be typical for that crowd density.

Millennium Bridge – A recent Vibration Problem (2000)

Lateral Natural Frequencies of different bridges is shown in the following figure

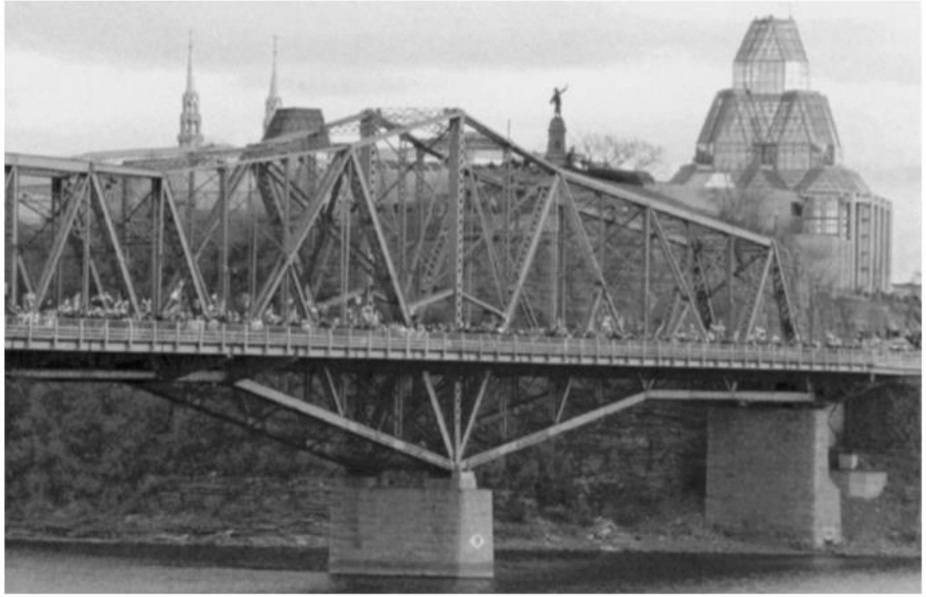


Millennium Bridge – A recent Vibration Problem (2000)

Previous observations of this behavior

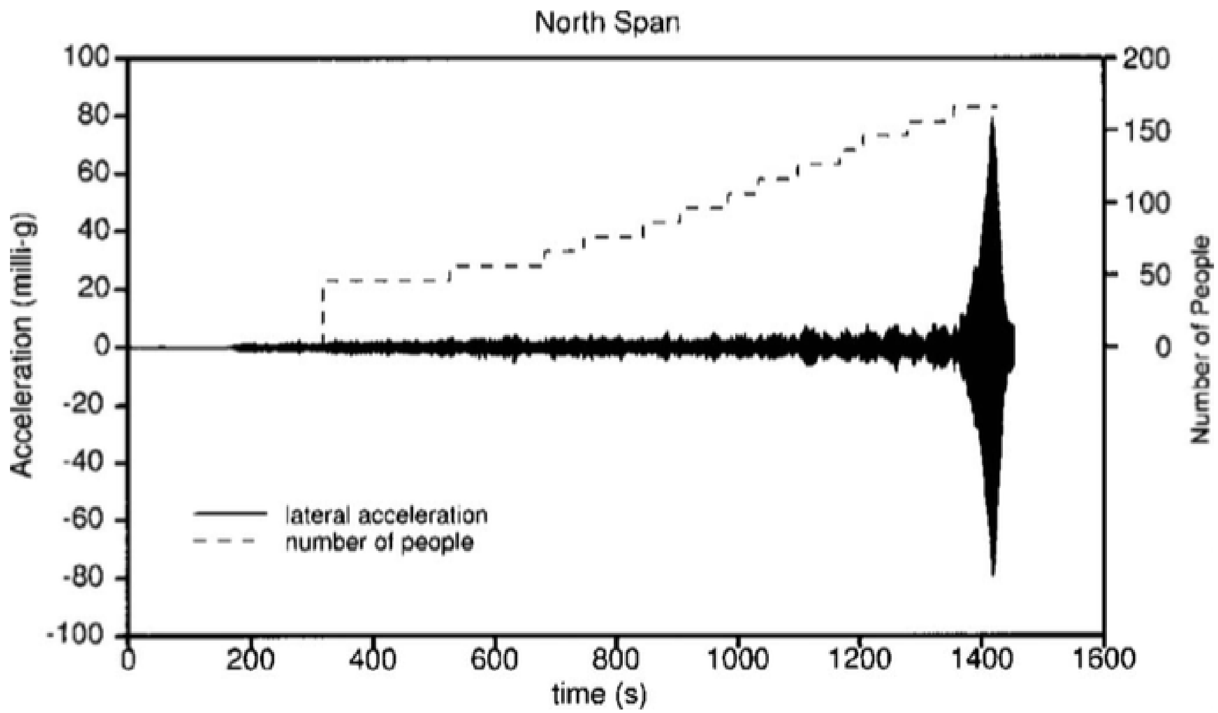
A 100 year-old footbridge in Ottawa experienced strong lateral vibrations in July 2000, also when subjected to crowd loading, in this case by spectators of a fireworks display.

Alexandra Bridge, Ottawa, Canada



Millennium Bridge – A recent Vibration Problem (2000)

The relation between the lateral acceleration of the bridge and the number of pedestrians is shown in the following figure



Question

How to create vibration and how to get rid of it (vibration isolation)?

Question

We will deal with Linear vibration problems only in this course.

Can you list the types of nonlinear vibration systems?

Vibration Analysis

Vibration Certifications

There are two institutes that gave certification in vibration: Vibration Institute and Mobius institute. Each of them classify the vibration analyst to four categories. Category IV is the most expert person and should have 5 years of vibration as a vibration analyst.

Vibration Institute

Mobius Institute

Vibration Certifications

1. Vibration Institute

Vibration Analyst Category	Recommended Experience for Exam Eligibility	Courses Recommended as Partial Preparation for Certification Exams* **						
		IMV	BMV	BRM	MVA	AVC	RDM	AVA
Category I	≥ 6 months	1						
Category II	≥ 18 months		2					
Category III	≥ 3 years			3	4			
Category IV	≥ 5 years					5	6	7
Training Course Cost		$1150	$1350	$1450	$1550	$1750	$1750	$1750

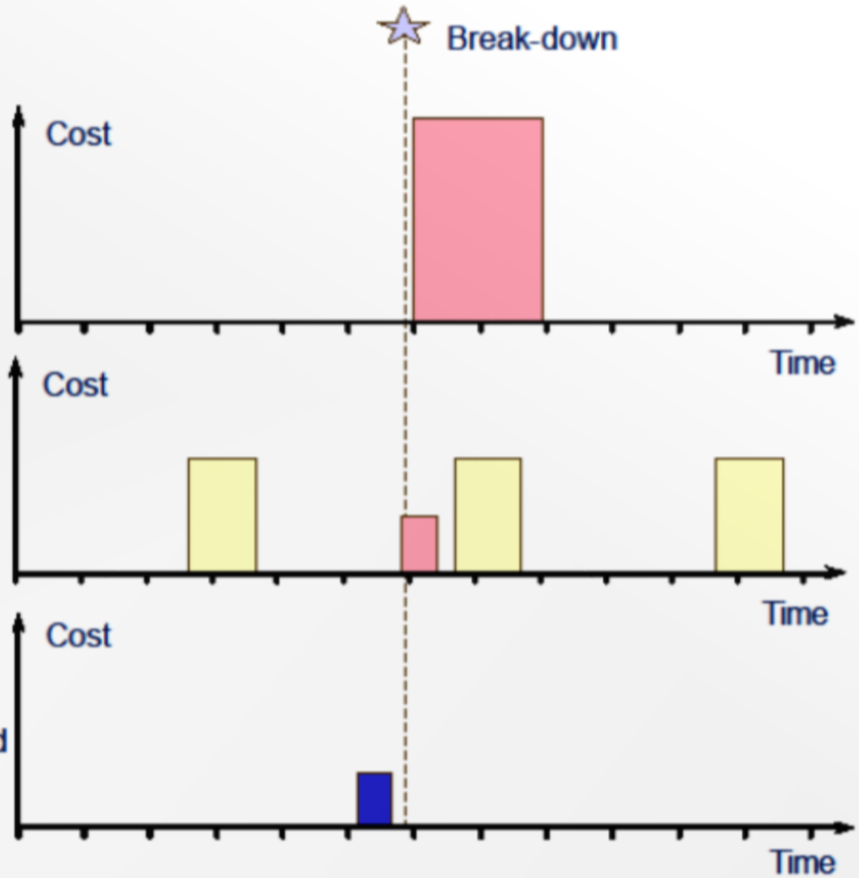
Types of Maintenance

Corrective Maintenance
(Run-to-breakdown)

Repair it when it fails

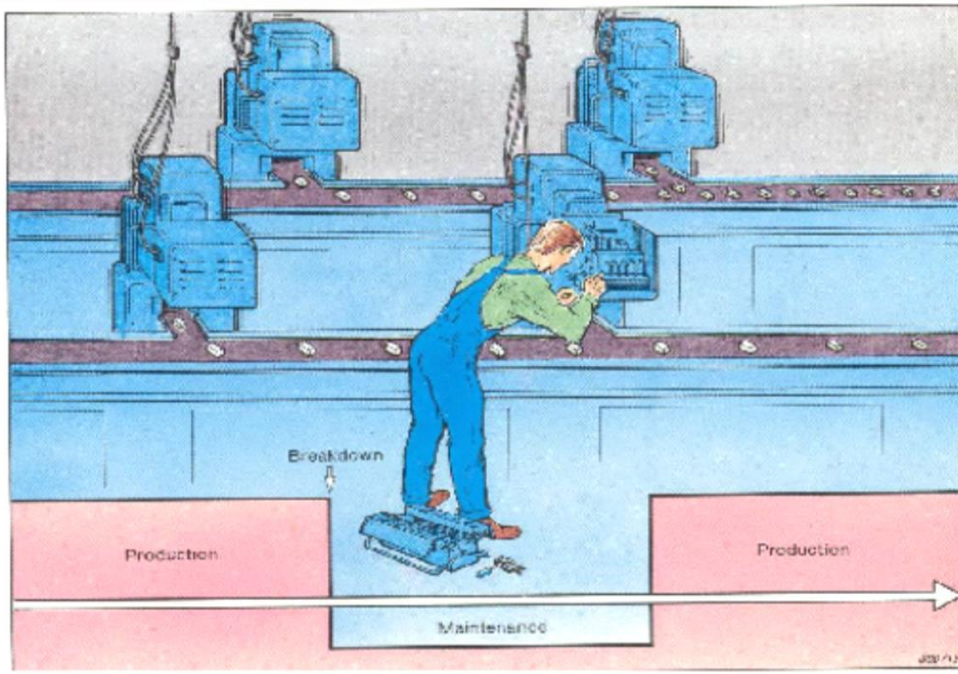
Preventive Maintenance
(Time Based Maintenance)
Maintenance at regular intervals

Predictive Maintenance
(On Condition Maintenance)
Problem detected before predicted failure.
Maintenance planned ahead



Corrective Maintenance

-Run to Breakdown-



Corrective Maintenance leads to:

- Secondary damage
- Safety risk
- Unplanned downtime
- Unplanned maintenance
- Product waste
- Spares inventory

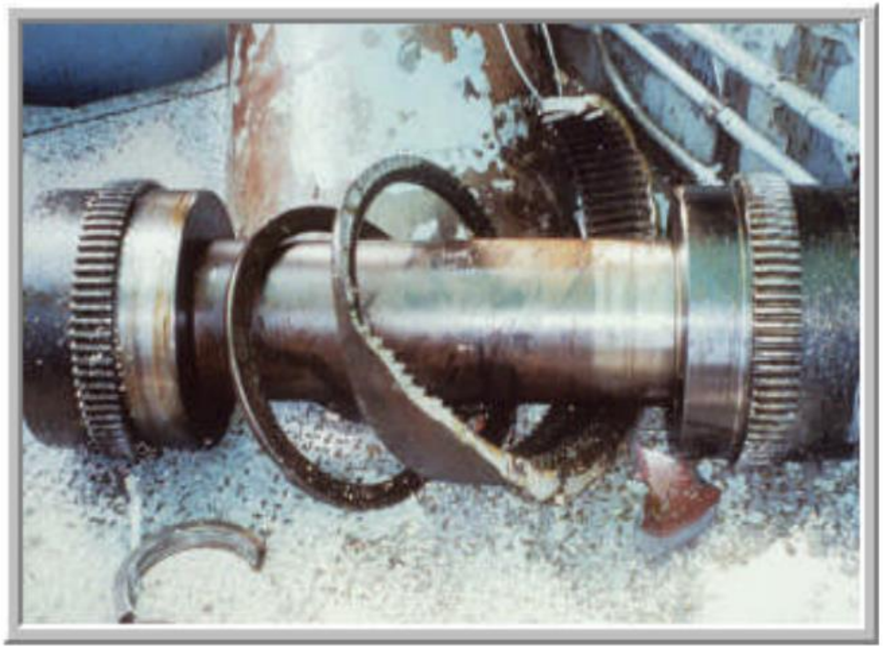
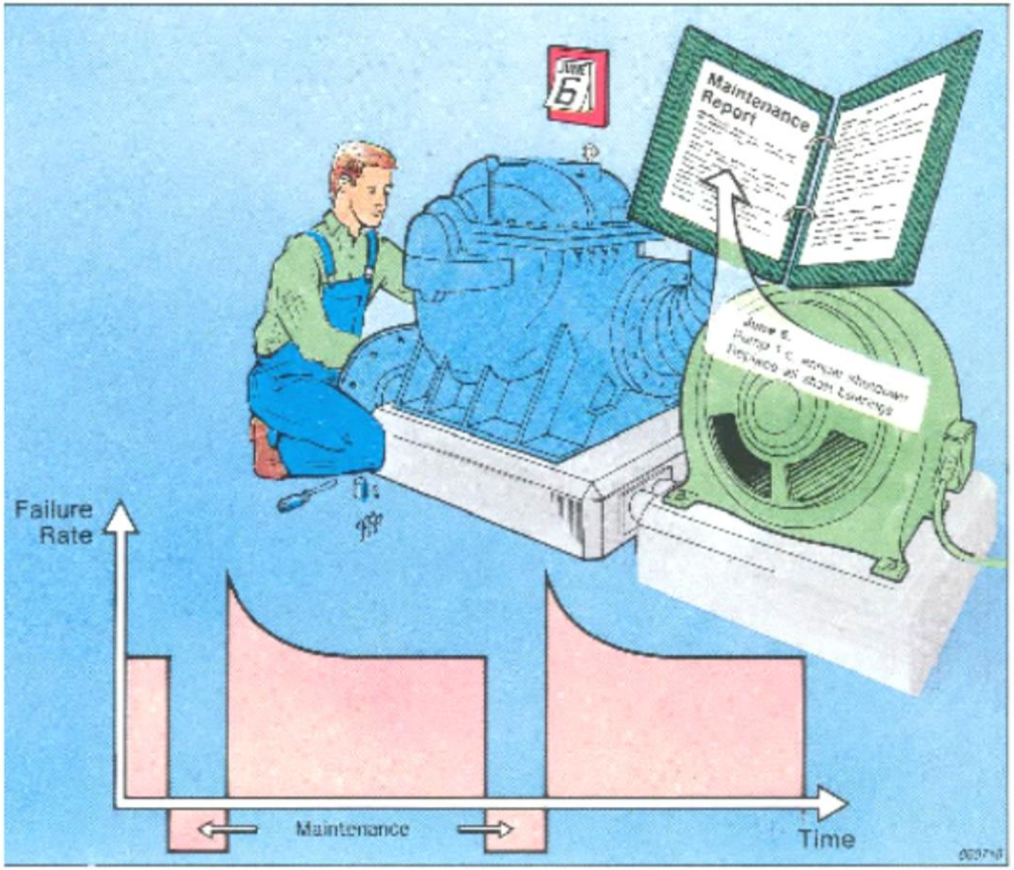


Figure 1-9 Run to Failure maintenance practices leads to very high maintenance costs.

Preventive Maintenance

Time Based Maintenance



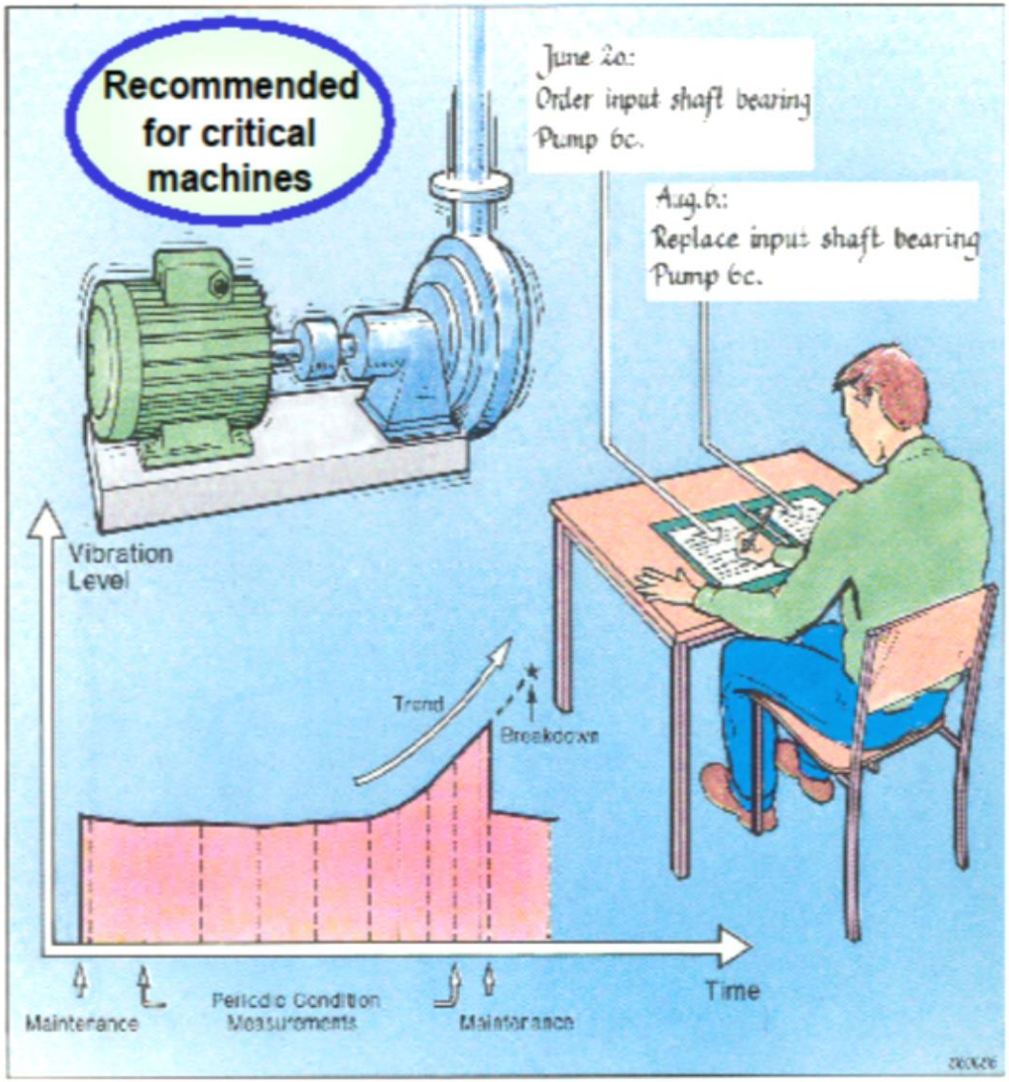
Not recommended for critical machines

Time-based Preventive Maintenance involves:

- **More frequent overhauls**
- **Risk of early failures**
- **Tampering with good machines**
- **Time consuming overhauls**
- **Experts needed for each overhaul**

Predictive Maintenance

On-condition -Maintenance



- Monitor the condition of the machine and predict when it would fail
- Plan maintenance ahead of time and save money
- Repair the machines only when they need to
- Focus overhauls only on faulty parts

- Higher plant availability, performance and reliability
- Greater safety
- Better product quality
- Attention to environment
- Longer equipment life
- Greater cost effectiveness

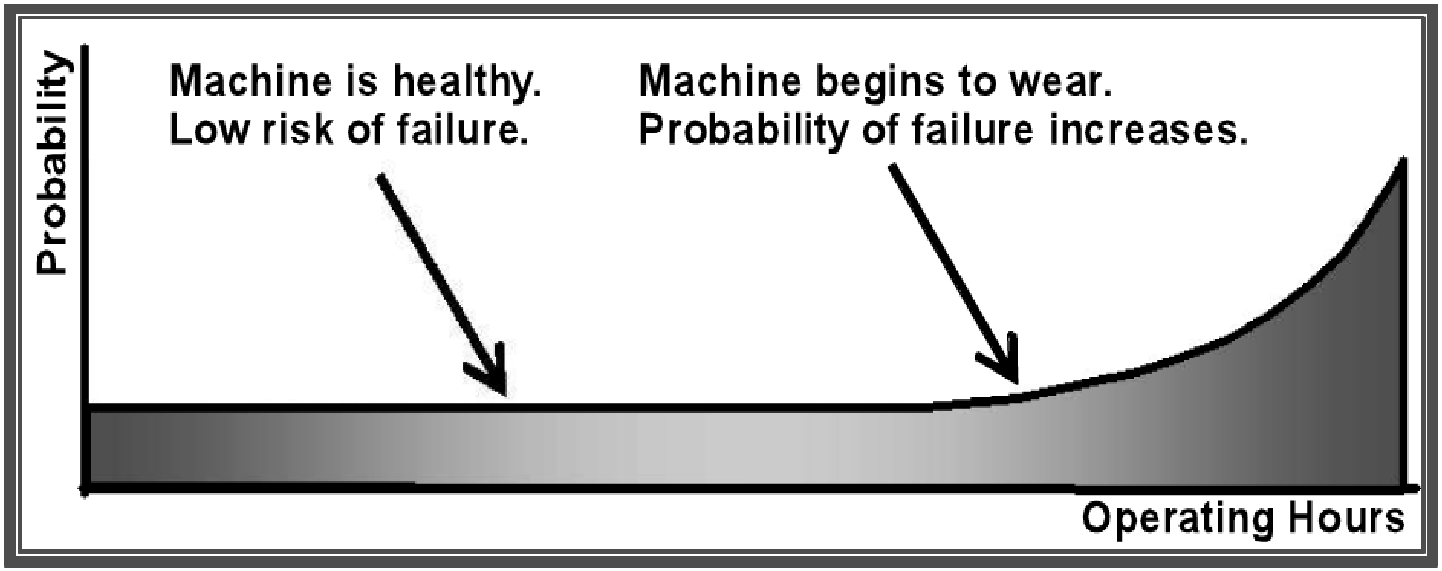


Figure 1-11 The assumption is that the probability of failure remains low for some period.

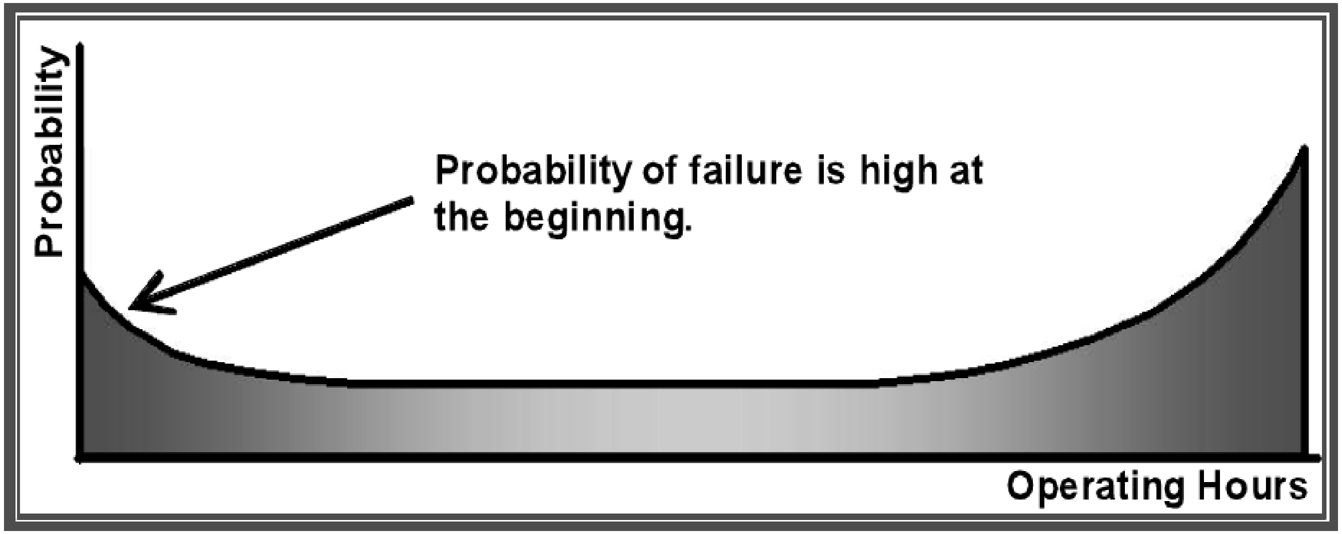


Figure 1-12 Probability of failure including Infant Mortality risks

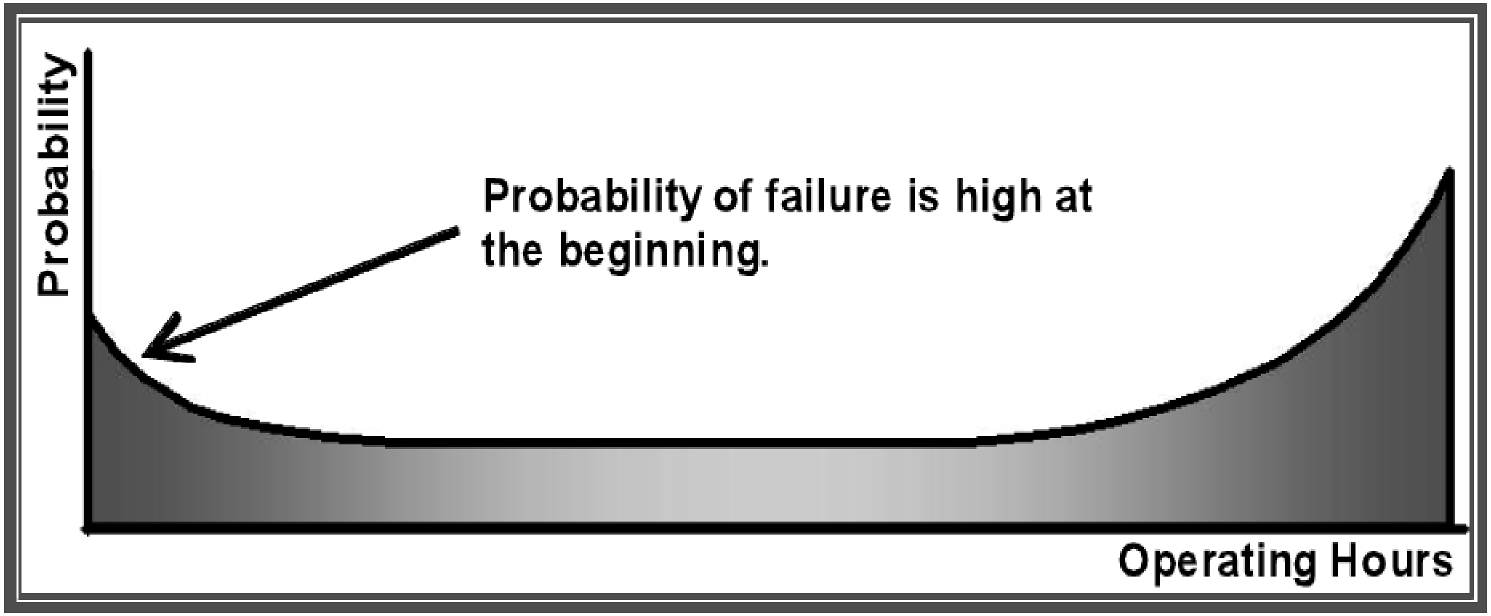


Figure 1-12 Probability of failure including Infant Mortality risks

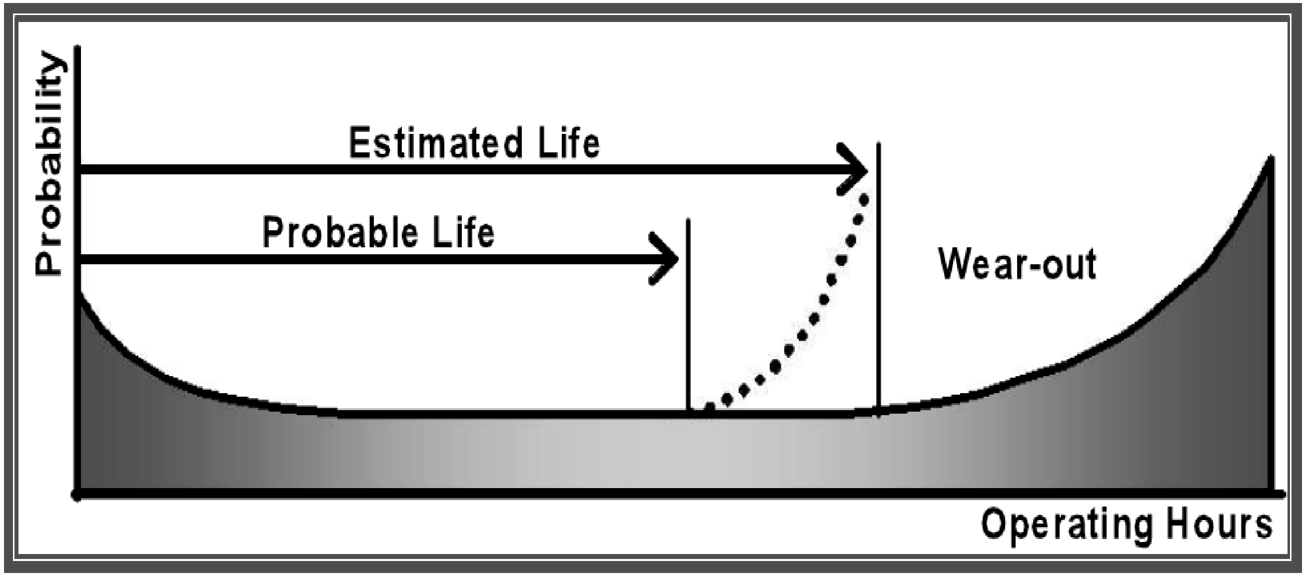


Figure 1-13 Probable Life and Estimated Life added to graph.

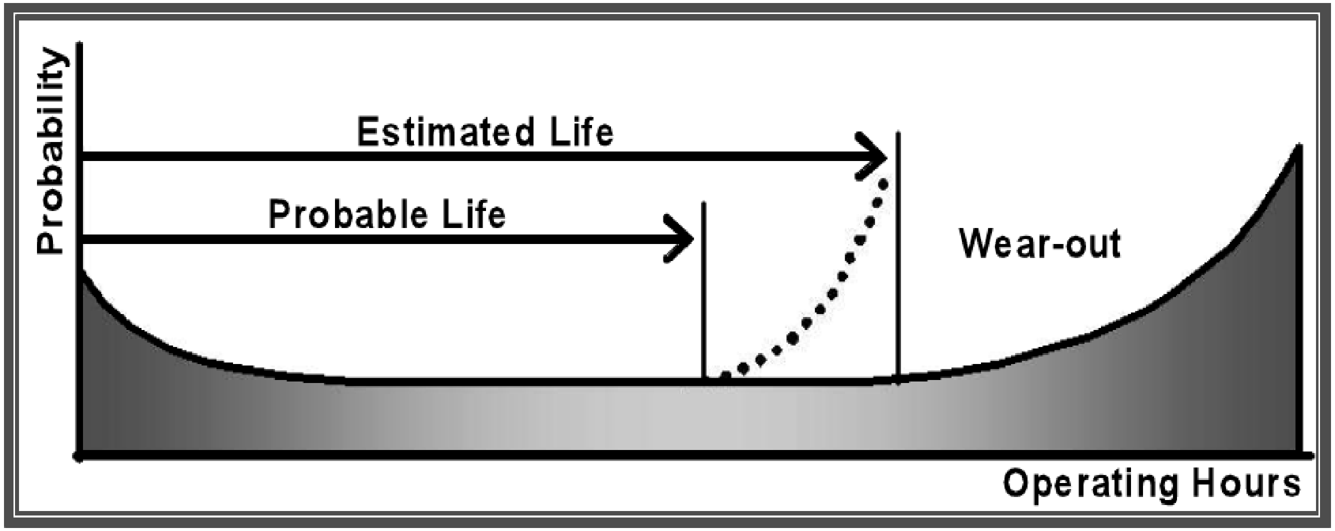


Figure 1-13 Probable Life and Estimated Life added to graph.

Figure 1-8 New philosophy…it is worth the time

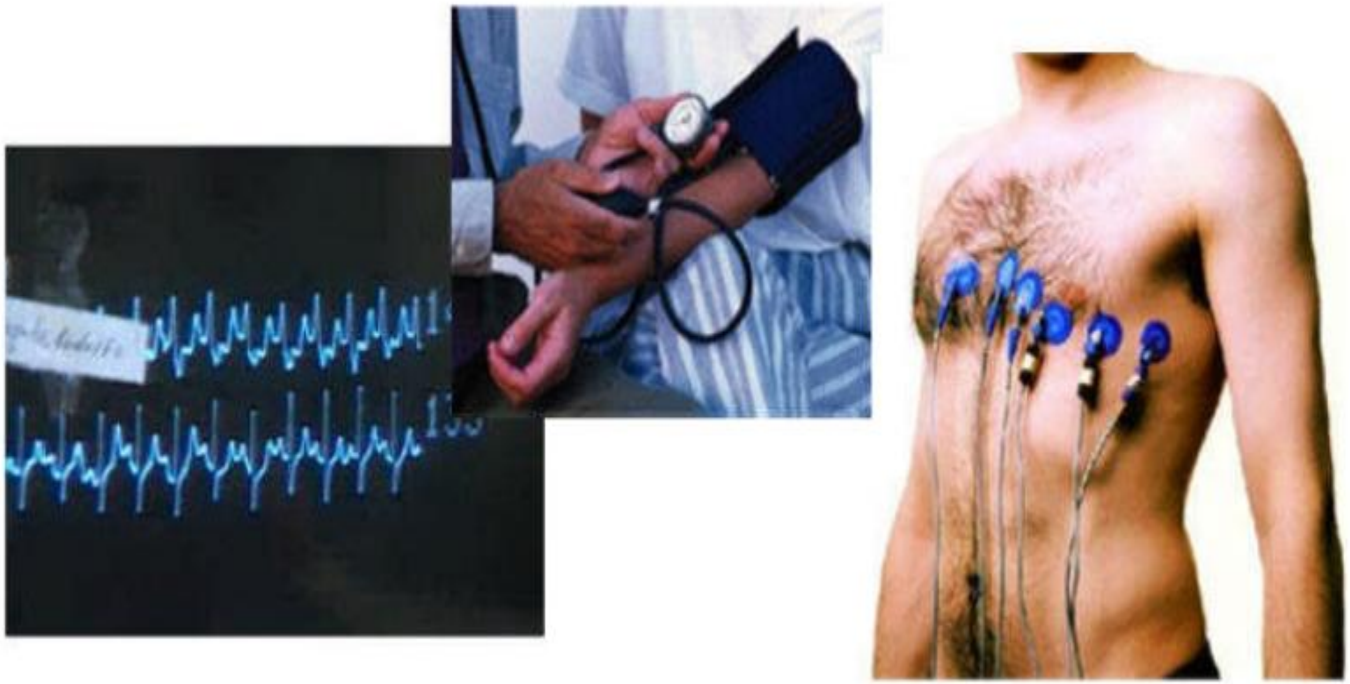


Figure 2-1 Various technologies are used to determine the state of our health

Infrared Camera

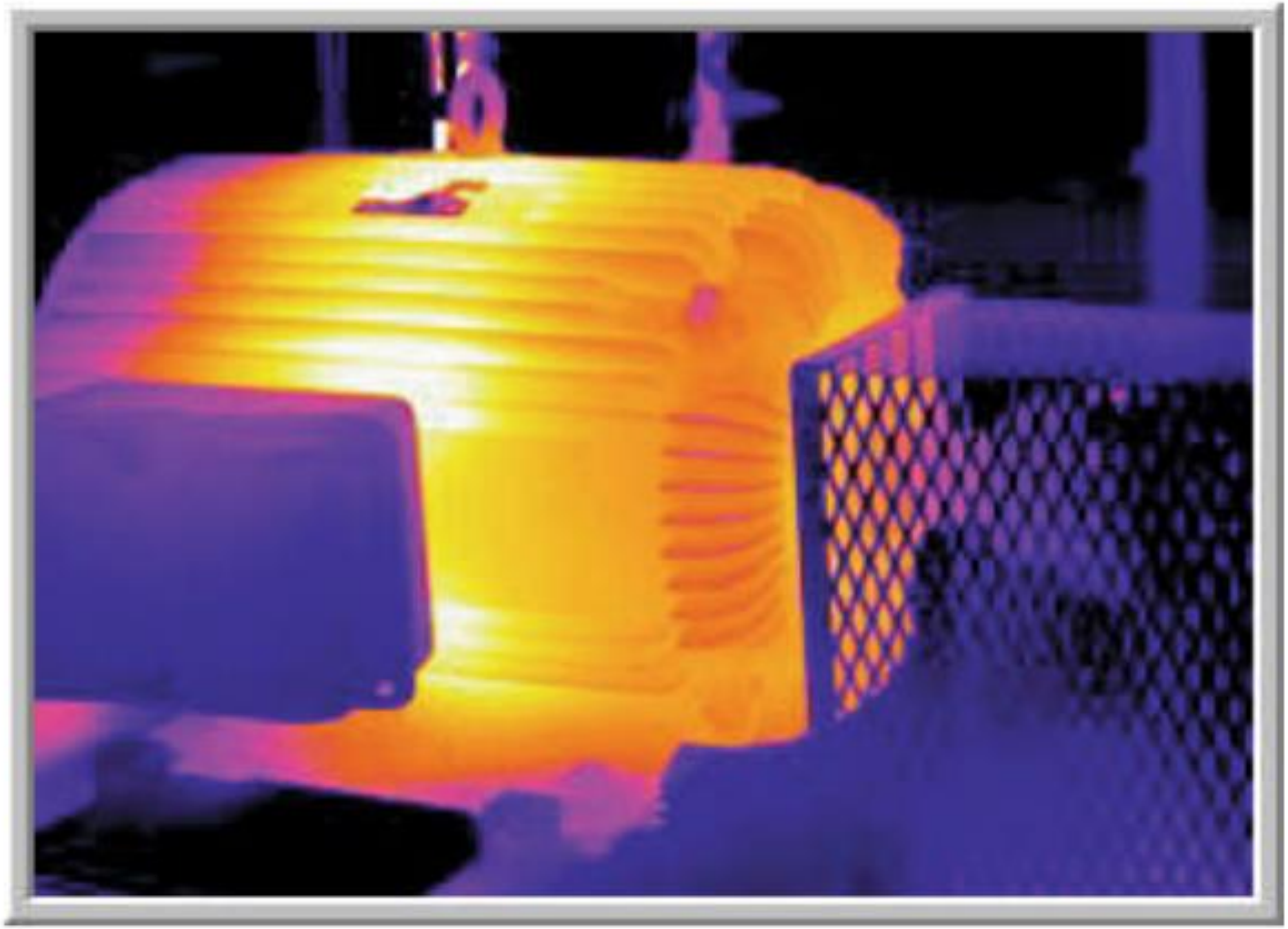


Figure 1-17 Infrared Thermography image of overheated motor

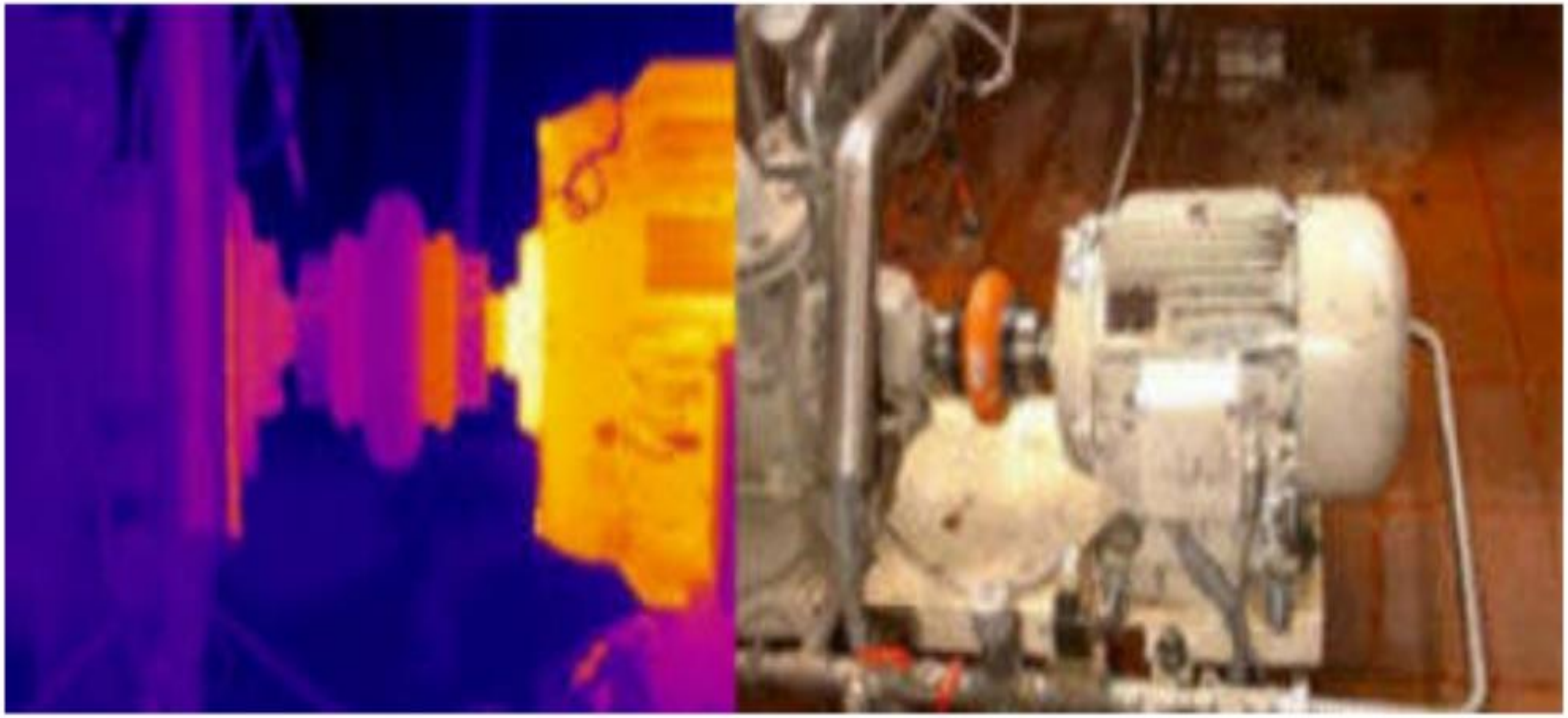


Figure 2-20 Thermographic and photographic image of overheated bearing

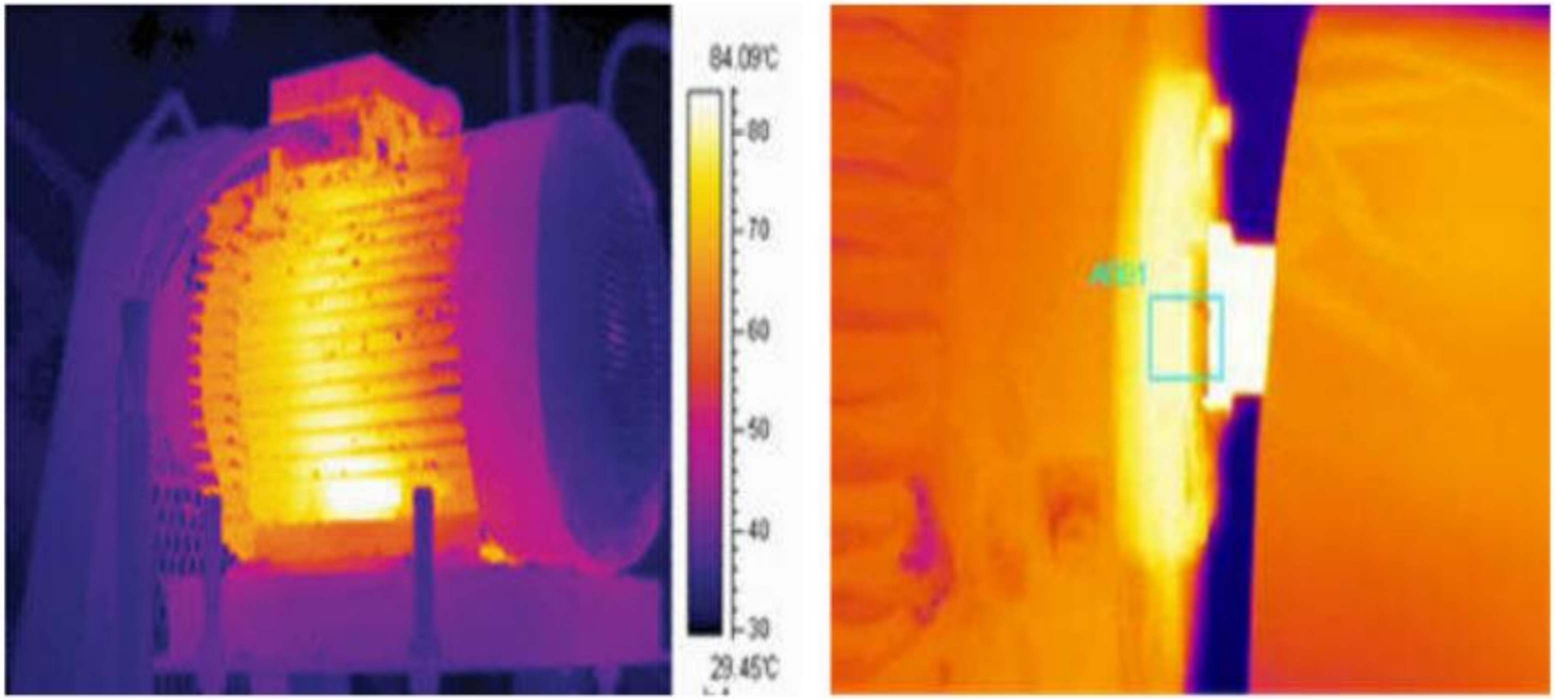


Figure 2-31 Thermographic and Photographic image of failed steam trap. Note the delta temperature of 20 degrees.

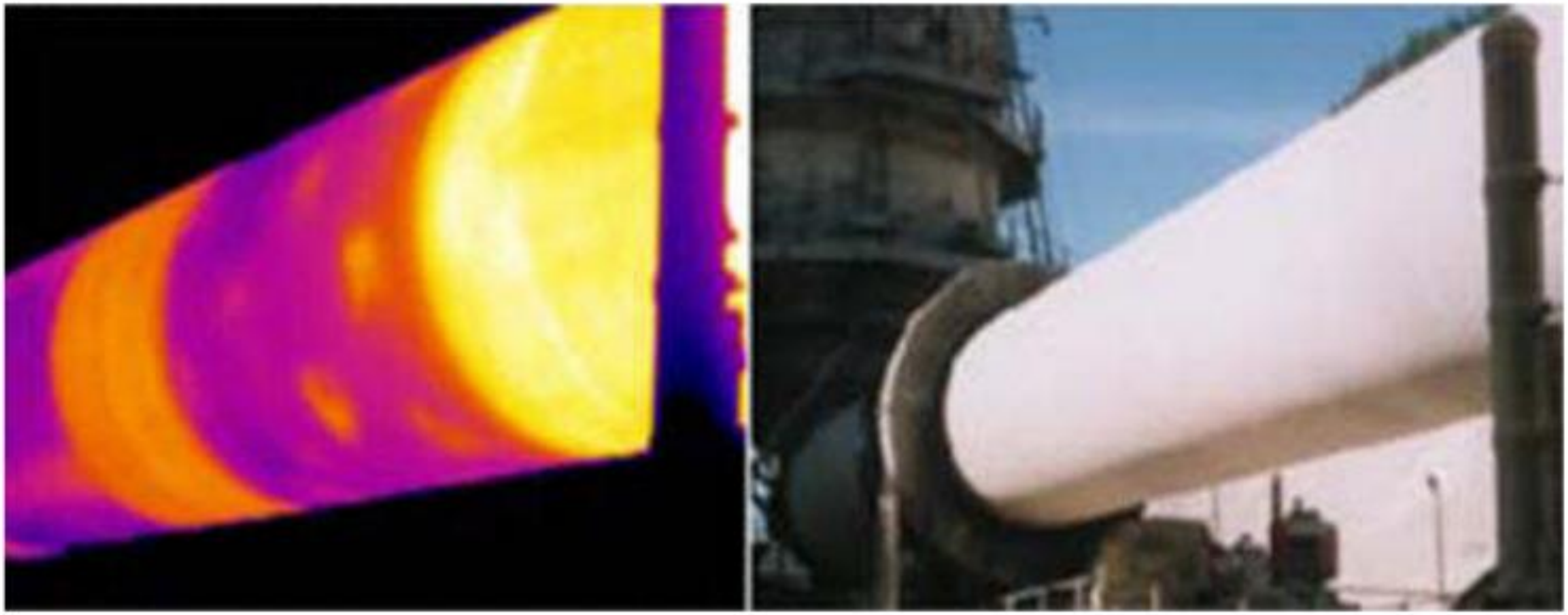


Figure 2-33 Lime kiln with hot areas indicating poor insulation.

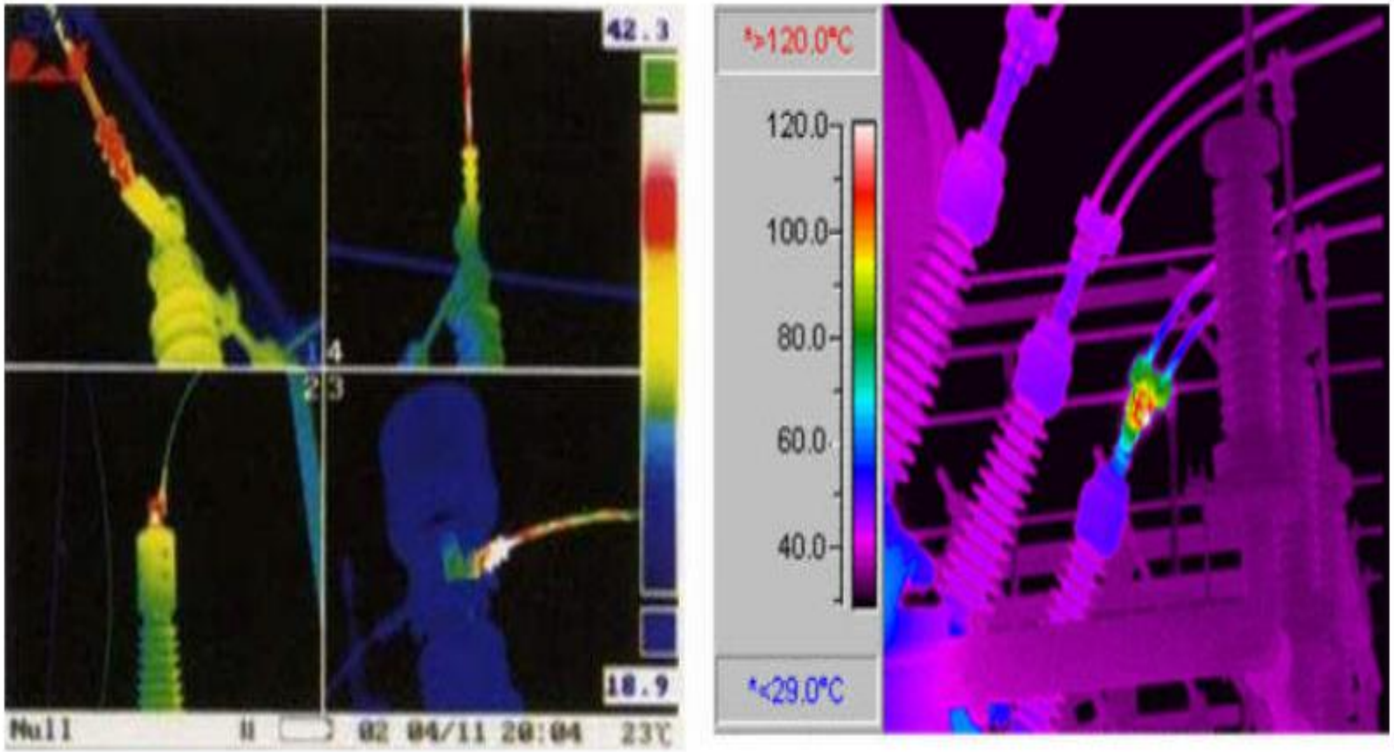
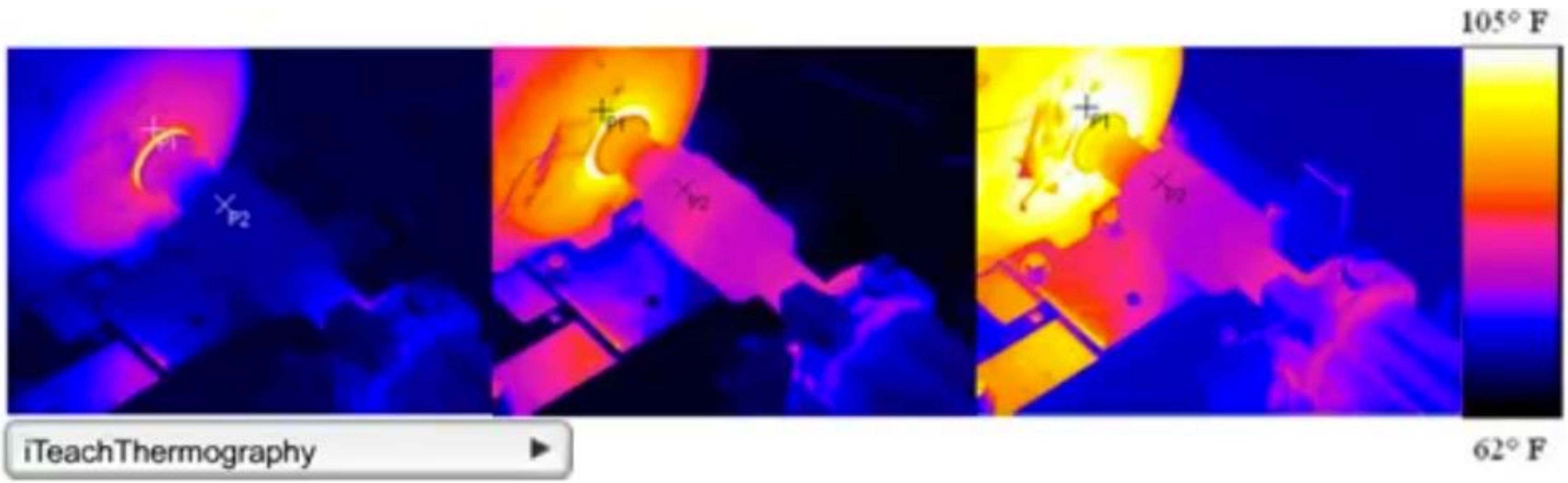


Figure 2-27 Loose connections and overloading can be detected. Overcome the effects of sun by scanning at night.


105° F
P1
P2
iTeachThermography
62° F

Oil Analysis

Figure 2-40

Oil Particle Analysis

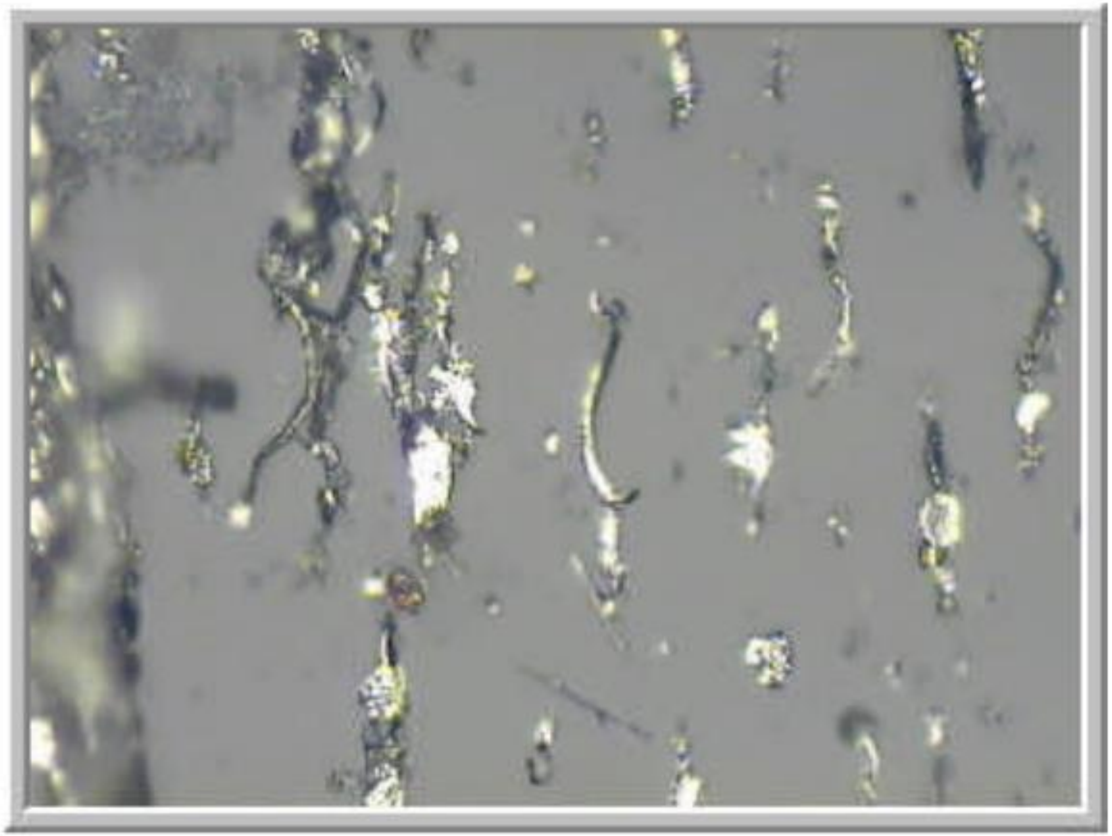


Figure 1-18 Wear Particles in Oil Sample

Vibration Analysis

Figure 1-24

Vibration Analysis

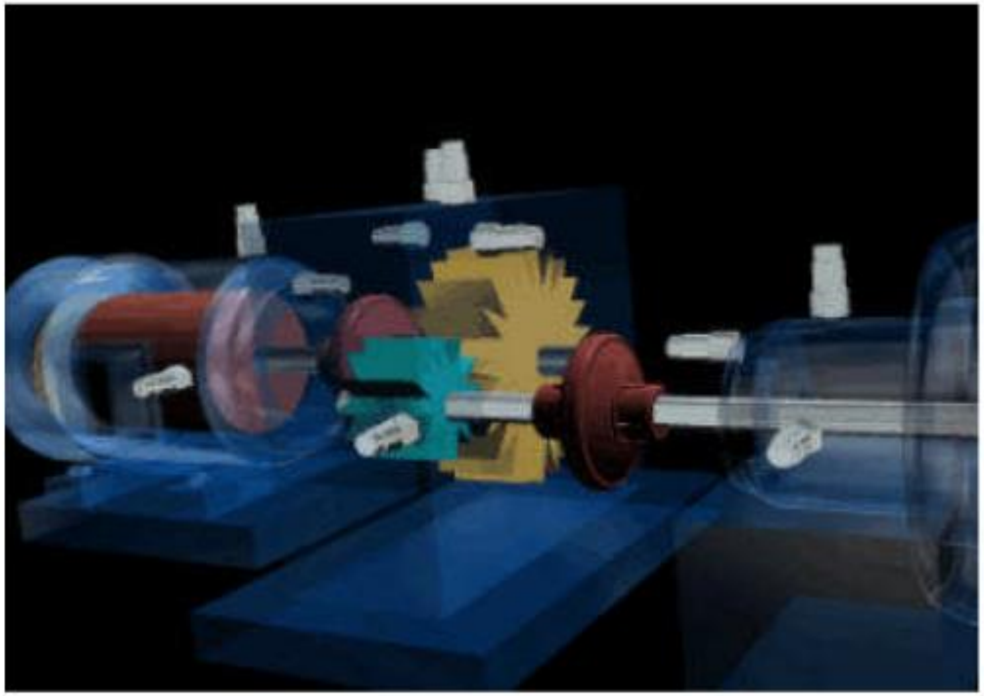
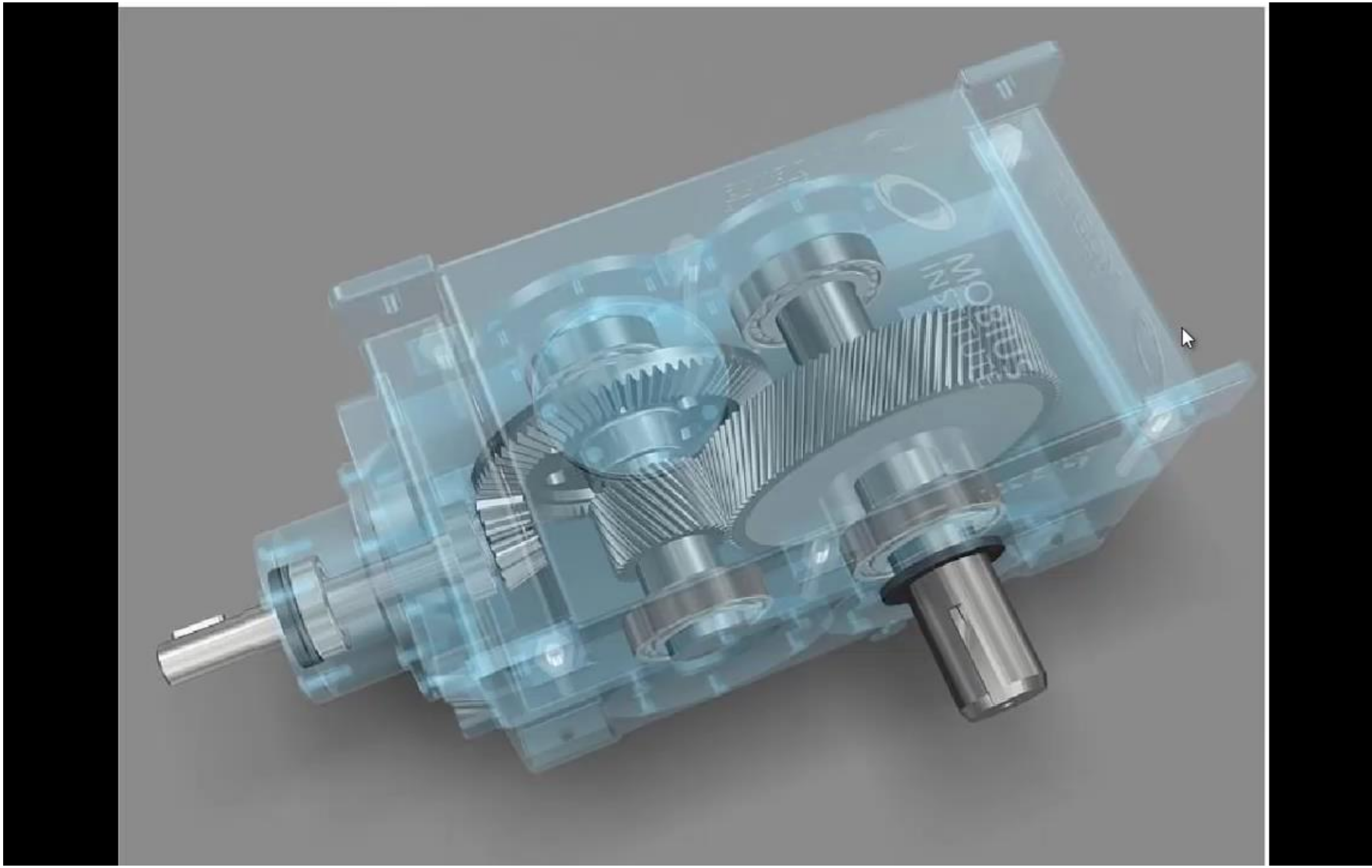


Figure 2-2 Various technologies let us see the condition inside a machine

Equipment failure happens – how do we avoid it?

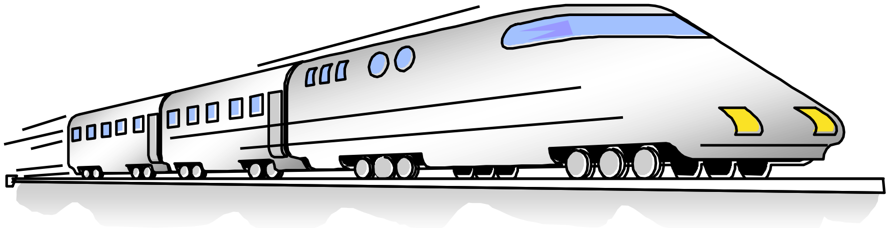

MOBIUS

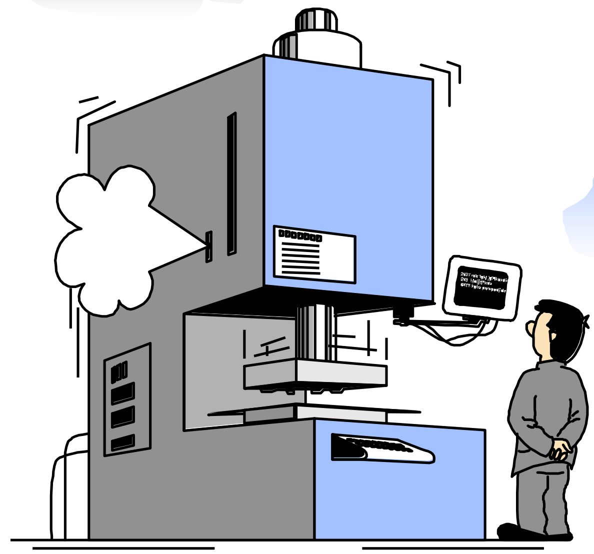
Vibration Analyzer

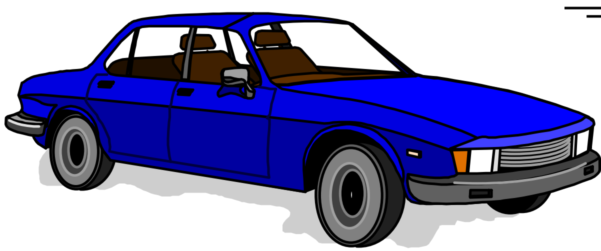
Vibration Analyzer

Vibration Analyzer

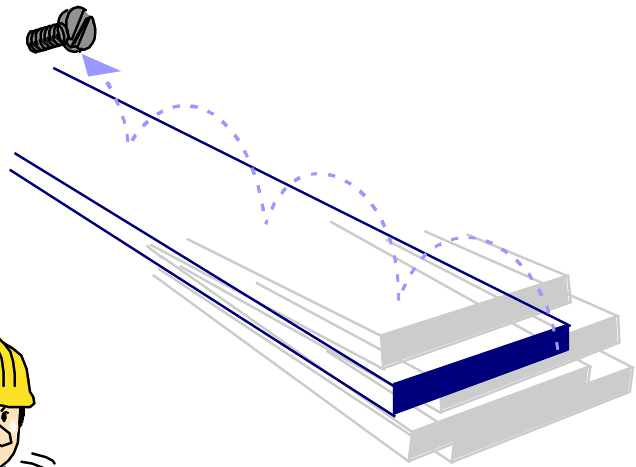
Vibration In Everyday Life

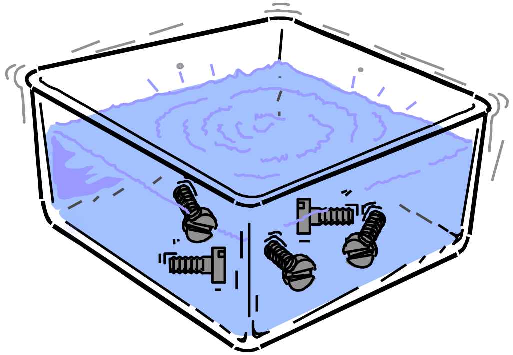


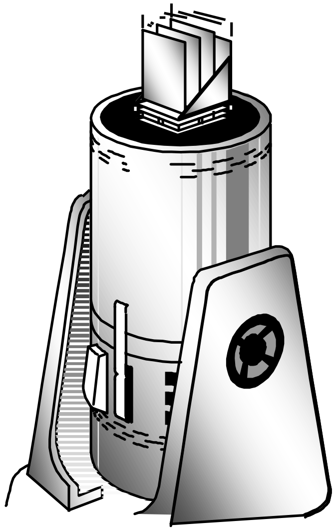




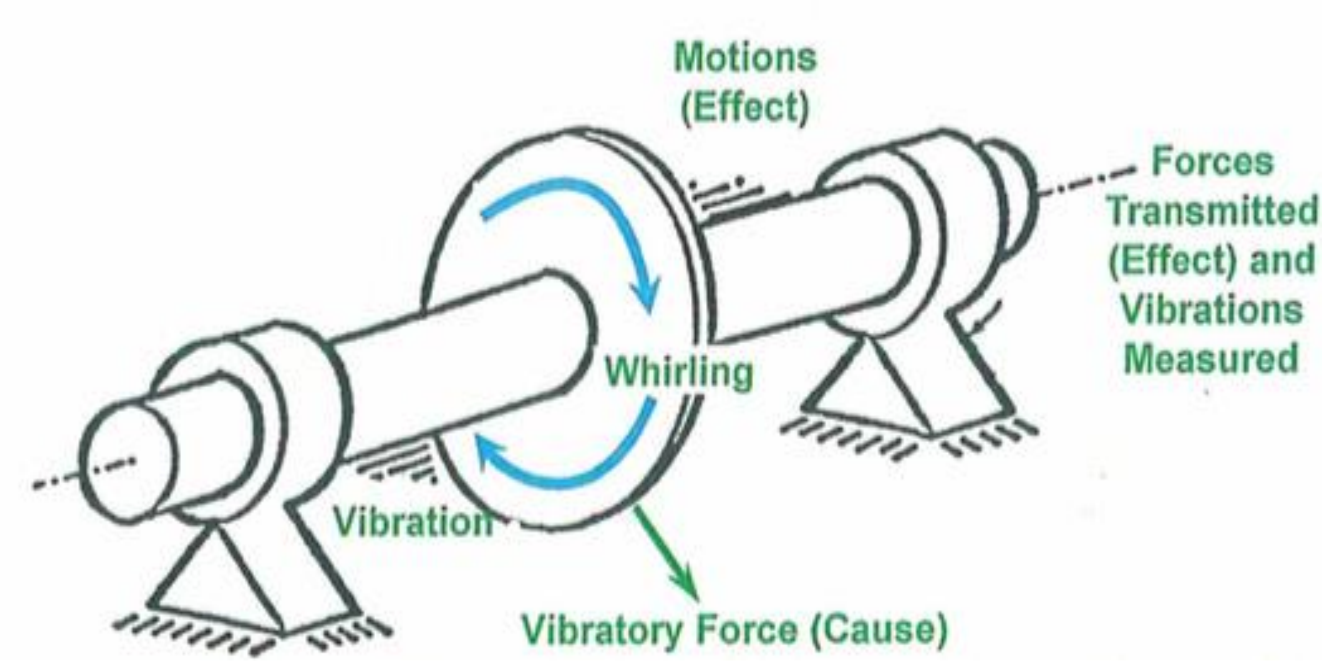
Useful Vibration







Cause and Effect Nature of Vibration



Acceptable limit of vibration

Overall levels of vibration are typically judged in terms of limits; e,g,, acceptance of new and repaired equipment, normal, surveillance and shut down.

The measured values are compared to the values in vibration standards such as

1) IRD 10816 Charts (Casing Measurements)
2) Bernhard Chart (Casing Measurements)
3) Vibration Institute Standards (Casing Measurements)
4) Update International Standards (Casing Measurements)
5) Blake Chart (Casing Measurements)
6) ISO 10816-1 Standard (Casing Measurements)
7) API 612 Standard (Shaft Displacement)
8) Dresser-Clark-Jackson Chart (Shaft Displacement)

Acceptable limit of vibration

1. ISO Standard

ISO 7919 Series	Mechanical vibration of non-reciprocating machines - Measurement on rotating shafts and evaluation criteria
7919-1:1996	Part 1: General Guidelines
7919-2: 2001	Part 2: Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min
7919-3: 1996	Part 3: Coupled industrial machines
7919-4: 1996	Part 4: Gas turbine sets
7919-5: 1997	Part 5: Machines set in hydraulic power generating and pumping plants
ISO 10816 Series	**Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts**
10816-1: 1995	Part 1: General Guidelines
10816-2: 2001	Part 2: Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min
10816-3: 1998	Part 3: Industrial machines with normal power above 15kW and nominal speeds between 120 r/min and 15000 r/min when measured in situ
10816-4: 1998	Part 4: Gas turbine sets excluding aircraft derivatives
10816-5: 2000	Part 5: Machines set in hydraulic power generating and pumping plants
10816-6: 1995	Part 6: Reciprocating machines with power ratings above 100 kW
10816-7[2]	Part 7: Rotodynamic pumps for industrial application

Table 1 • ISO Standards for Evaluation of Vibration Severity[1]

Acceptable limit of vibration

2. API Standard

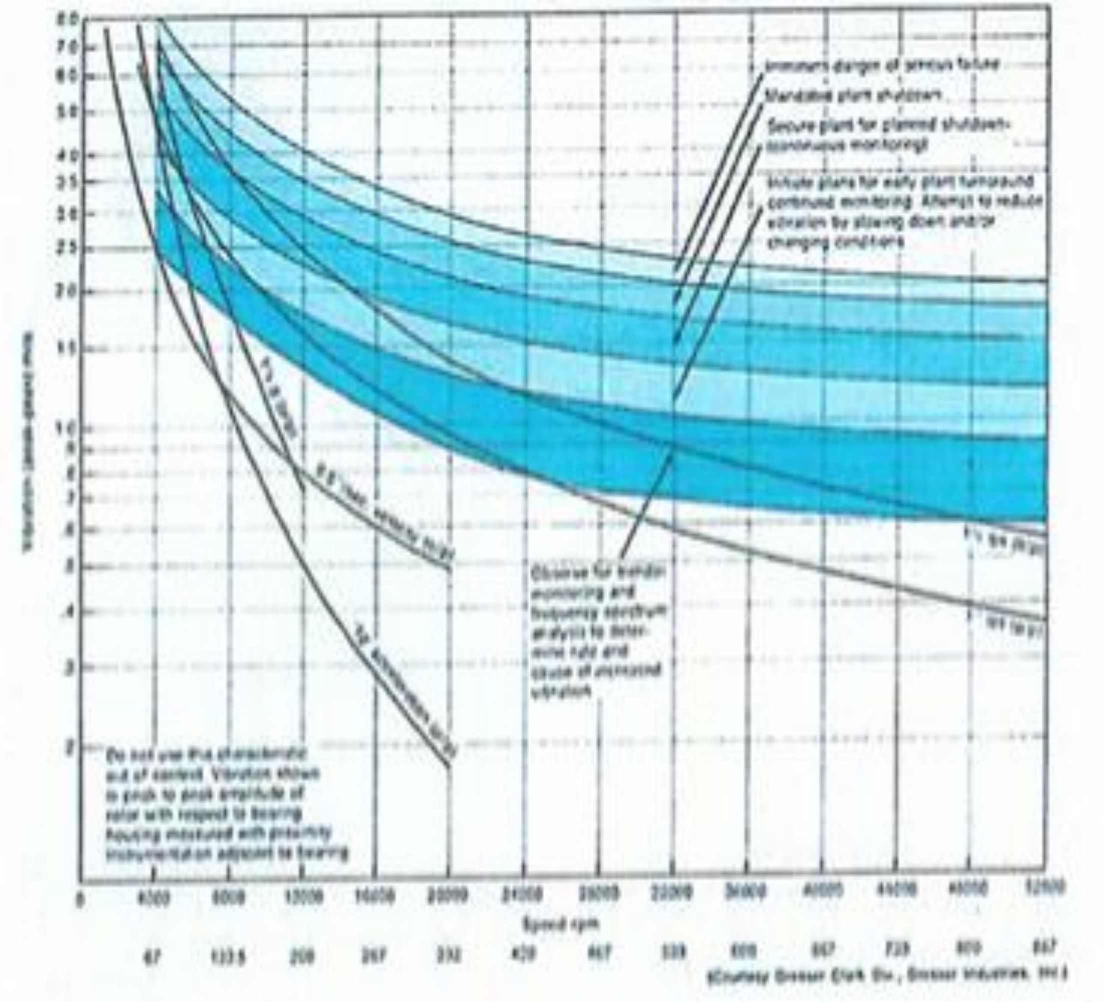
API produces a wide range of documents, including reference standards which are well suited for shop testing of new and rebuilt machinery. Note that these standards generally apply to equipment for use in the petrochemical industries. Table 4, below, shows a selection of API standards.

Equipment Type	API Standard	Acceptance Test	Other Requirements
Pumps	610 (9TH edition March '03)	Shaft Relative + Casing	Vertical Pump (0.20 ips pk)
Fans	673 (2ND edition November '01)	Casing (0.1 ips pk)	
Steam Turbines	612 (4TH edition June '95)	Shaft Relative (mil pk-pk)	4 hour run in test required
Gears	613 (5TH edition March '03)	Casing (0.15 ips pk)	Unbalance 4 W/N oz-in
Centrifugal Compressors	617 (7TH edition July '02)	Shaft Relative (mil pk-pk)	4 hour run in test required
Screw Compressors	619 (3RD edition June '97)	Shaft Relative (mil pk-pk)	Unbalance 4 W/N oz-in
Induction Motors (≥ 250 hp)	541 (4TH edition March '03)		Unbalance 4 W/N oz-in

Table 4 • Sample API Standards for Acceptance Testing

Acceptable limit of vibration

3. Shaft vibration for turbomachinery (measuring displacement) compare to Dresser Clark chart.



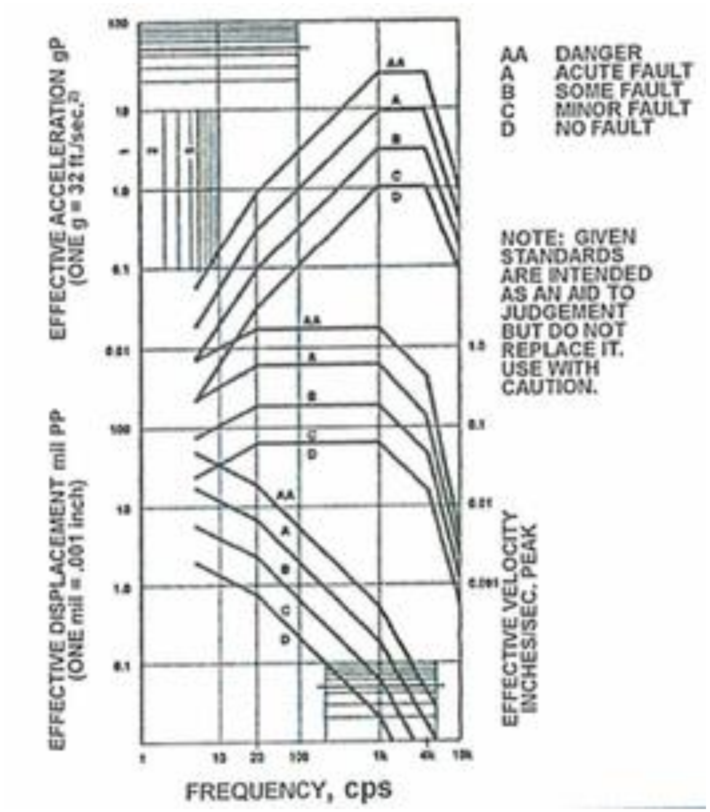
Acceptable limit of vibration

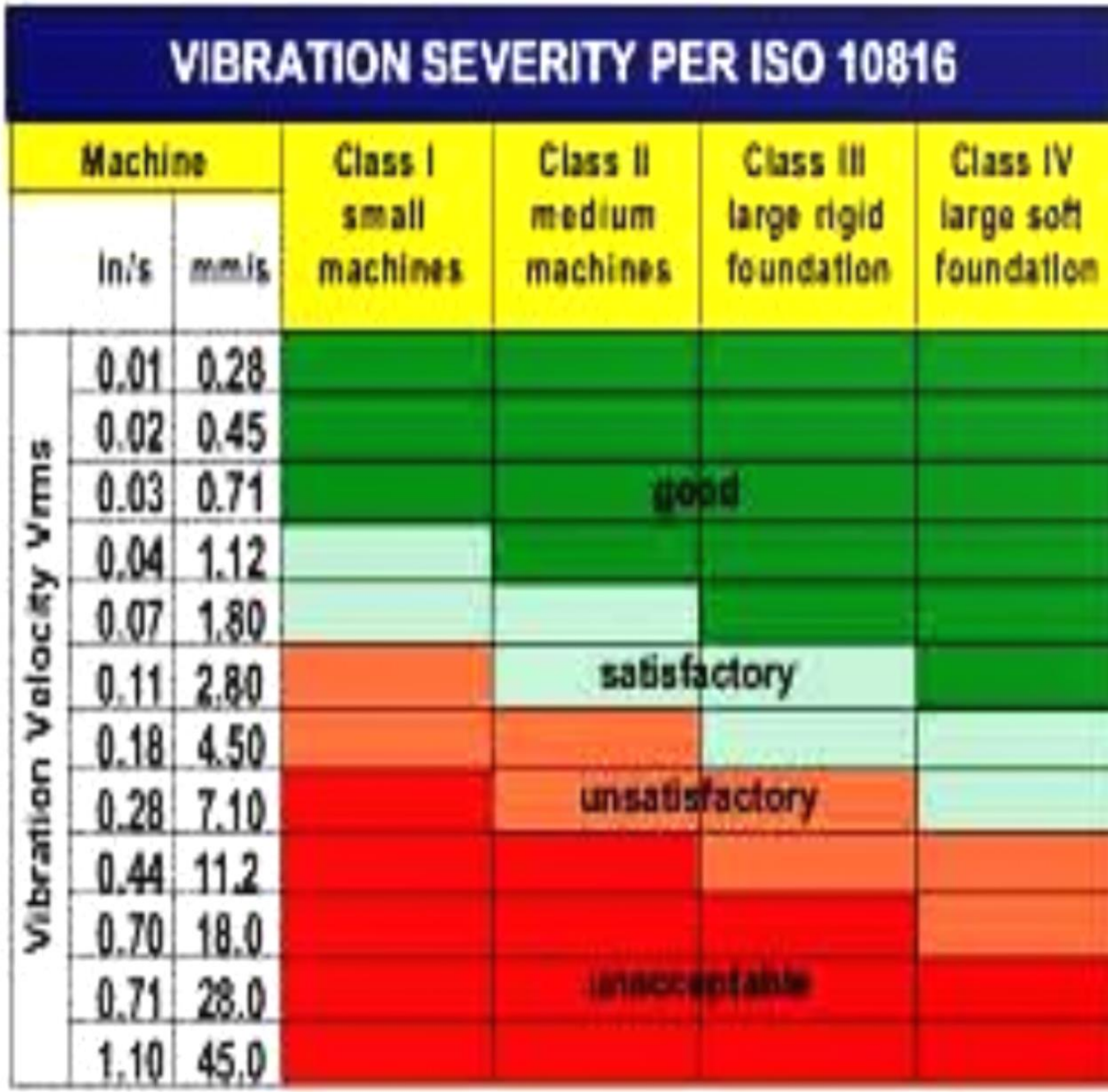
4. FLUID-FILM Bearing vibration (compare relative vibration of the rotor to the clearance in the bearing), compare to Vibration Institute tables.

MAINTENANCE ACTION	ALLOWABLE R/C	
	3,600 RPM	10,000 RPM
Normal	0.3	0.2
Surveillance	0.3 - 0.5	0.2 - 0.4
Shut down at next convenient time	0.5	0.4
Shut down immediately	0.7	0.6

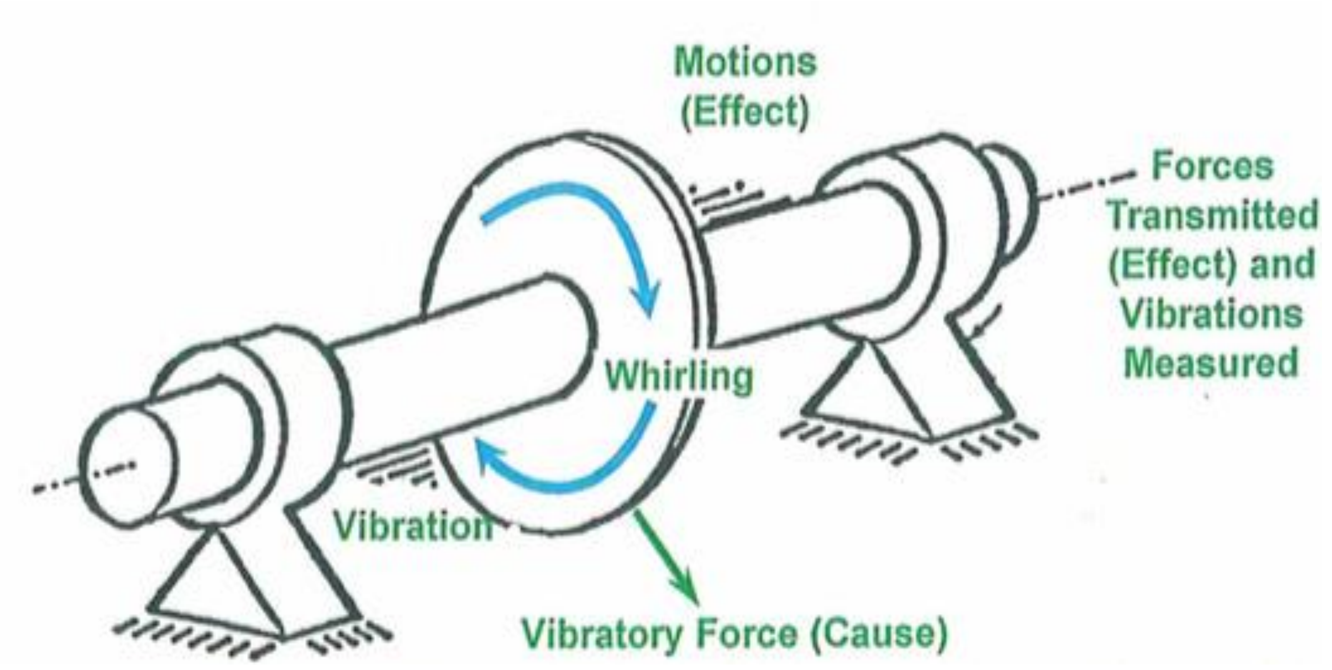
Acceptable limit of vibration

5. Casing Vibration (accelerometers or velocity transducers placed as close to the bearing as possible). Compare to tables or Blake chart.



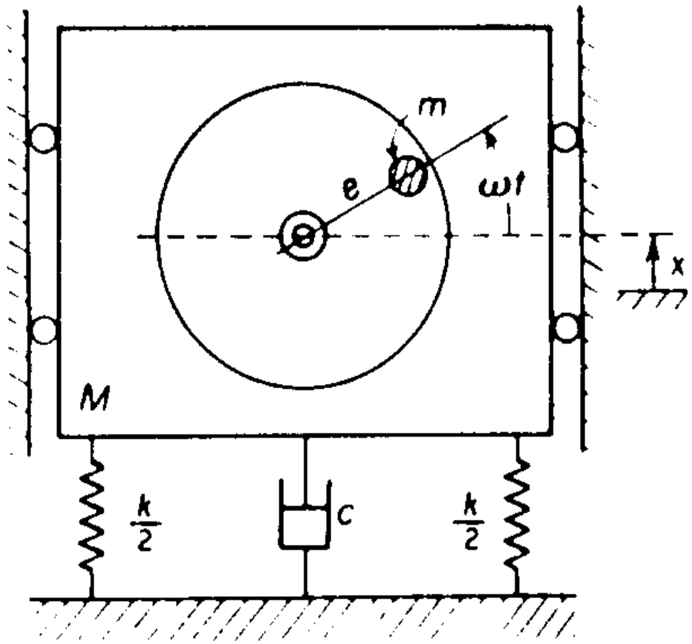

VIBRATION SEVERITY PER ISO 10816
Machine
in/s
mm/s
Class I small machines
Class II medium machines
Class III large rigid foundation
Class IV large soft foundation
Vibration Velocity Vrms
0.01 0.28
0.02 0.45
0.03 0.71
0.04 1.12
0.07 1.80
0.11 2.80
0.18 4.50
0.28 7.10
0.44 11.2
0.70 18.0
0.71 28.0
1.10 45.0
good
satisfactory
unsatisfactory
unacceptable

Cause and Effect Nature of Vibration



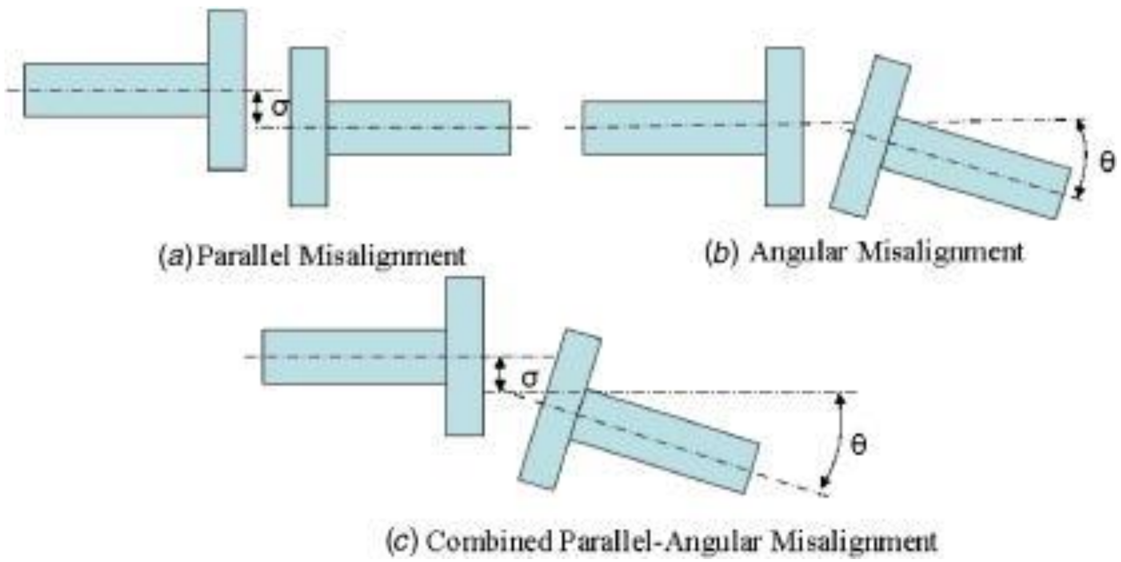
Causes of Vibrations

1. Mass unbalance



Causes of Vibrations

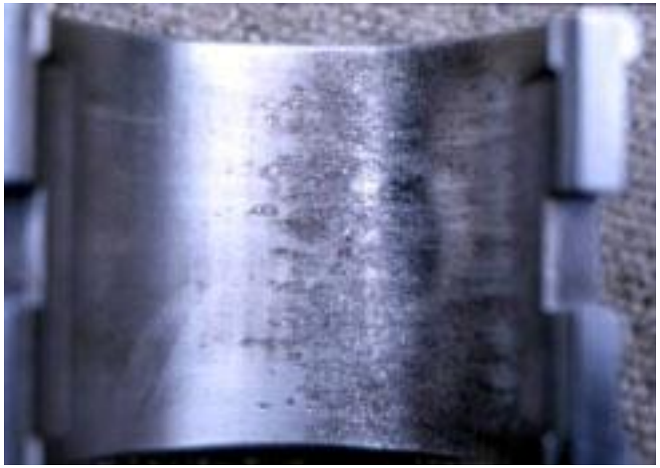
2. Misalignment



Causes of Vibrations

3. Fluid-film bearing wear

JOURNAL BEARING



WEAR IN PADS

Causes of Vibrations

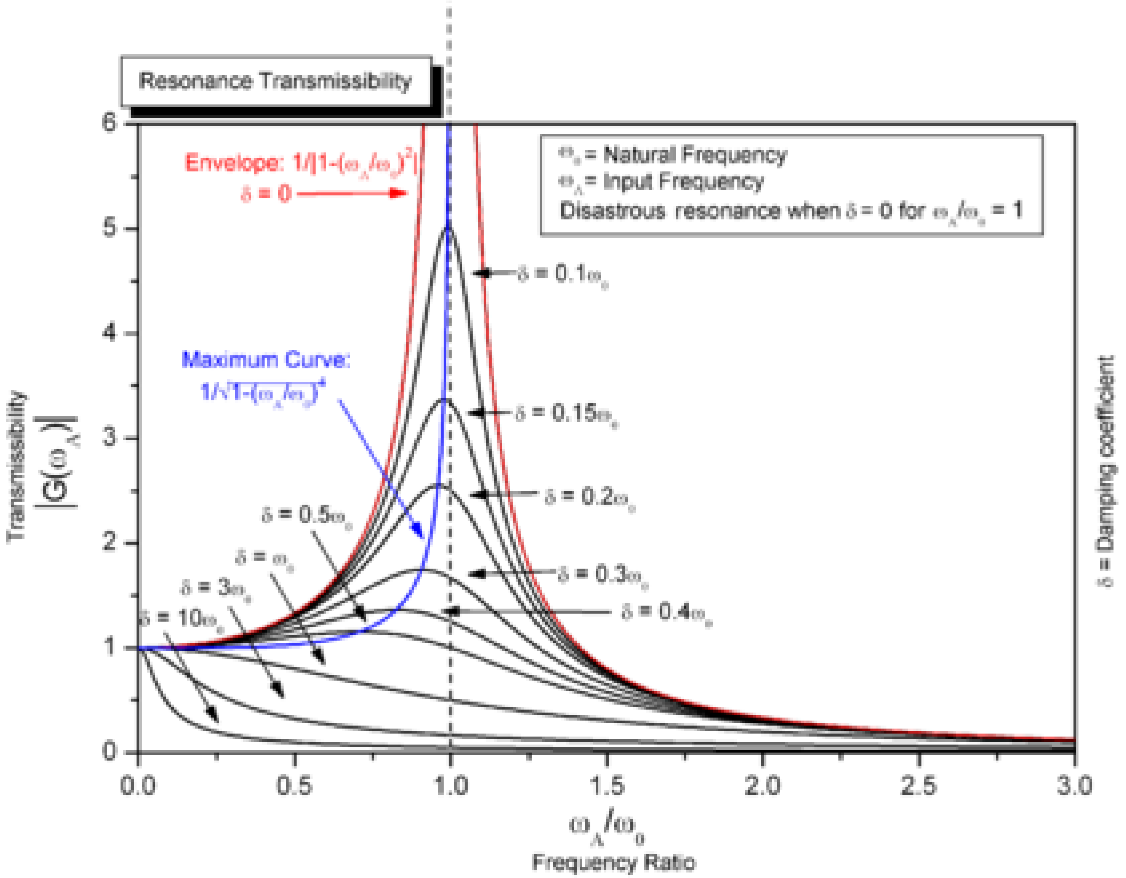
3. Fluid-film bearing wear

Thrust Bearing

WEAR IN PADS

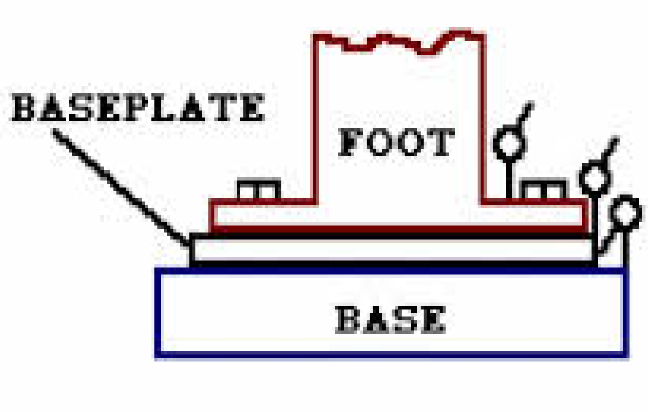
Causes of Vibrations

4. Resonance



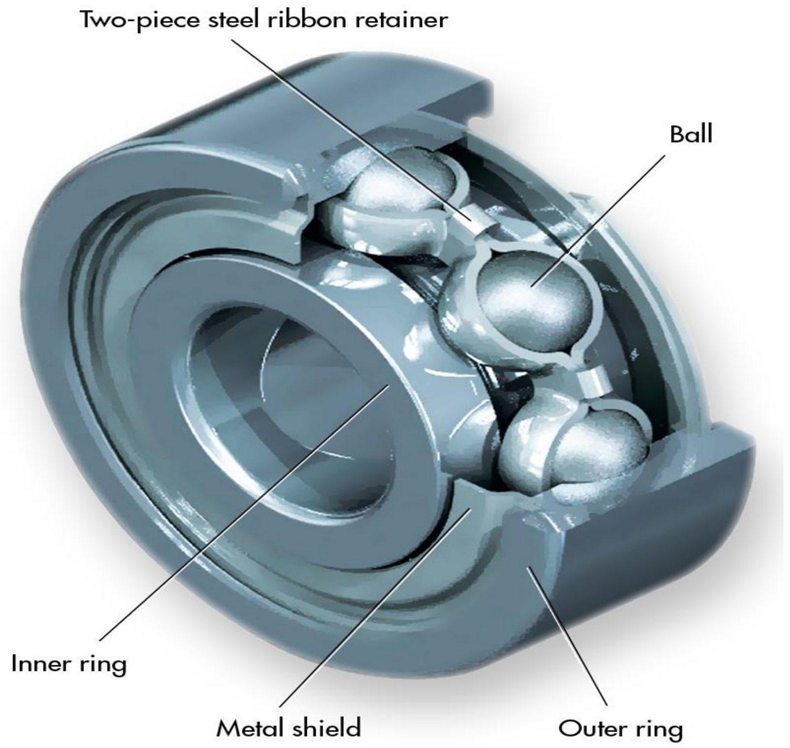
Causes of Vibrations

5. looseness



Causes of Vibrations

6. Rolling element bearing (outer race defect – inner race defect – ball defect – excessive internal clearance)

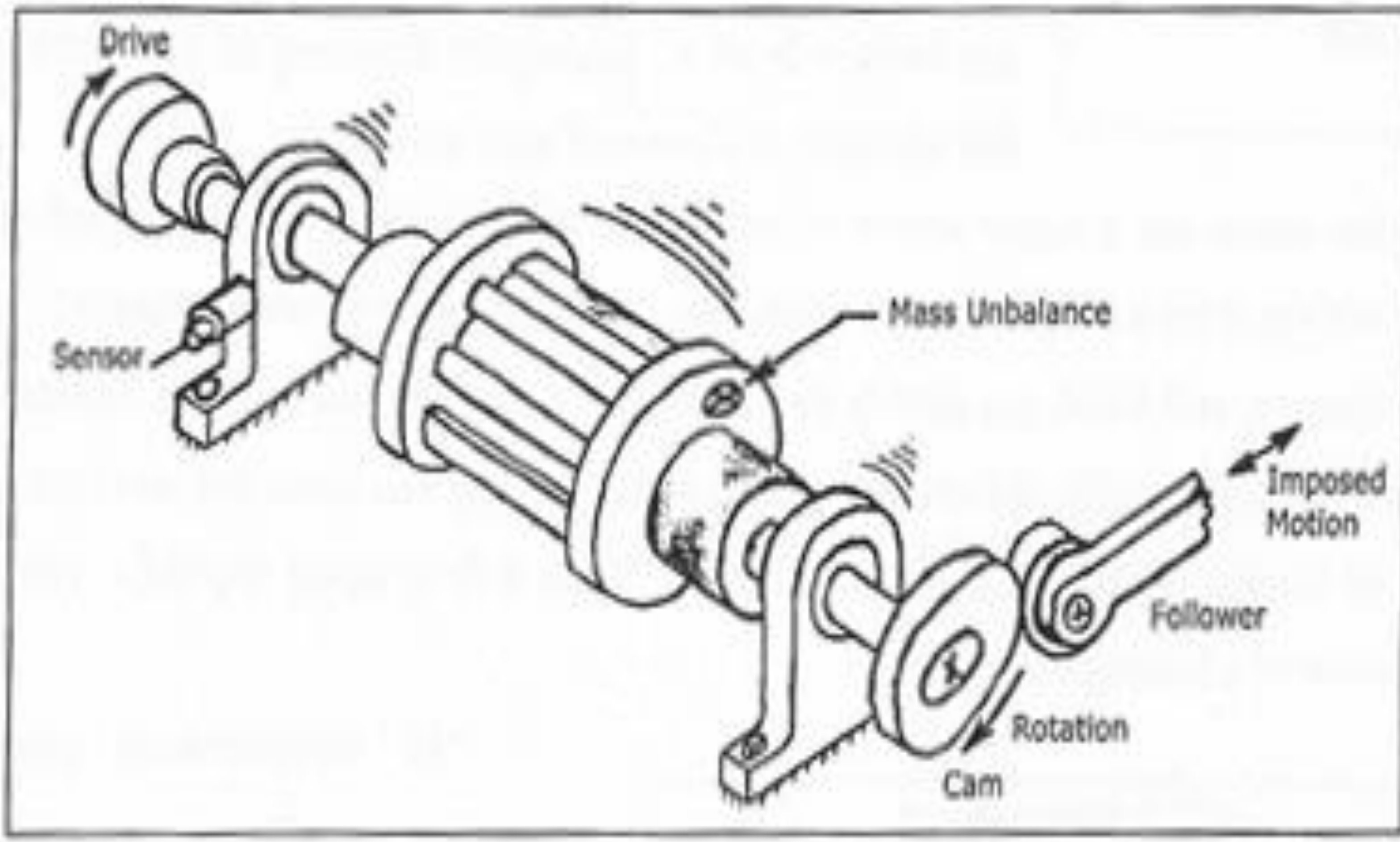


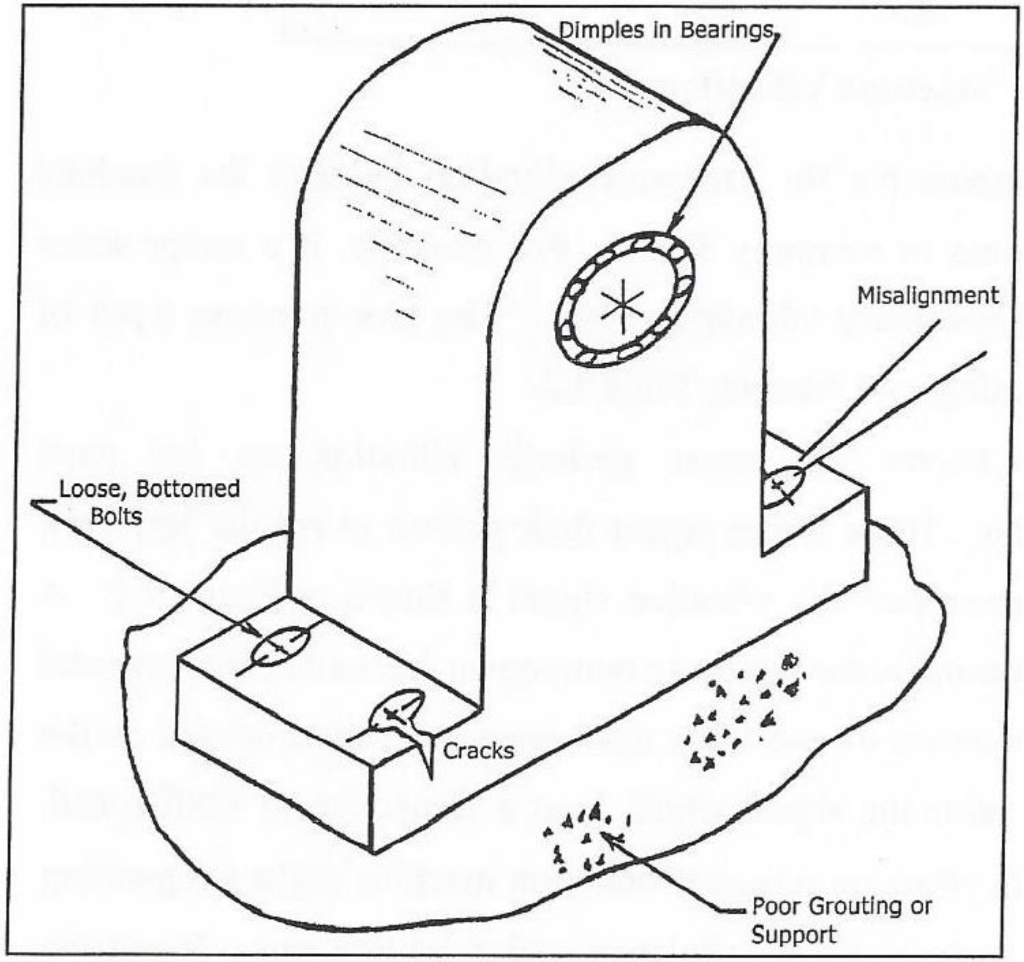
Vibration Certifications

1. Vibration Institute

BODY OF KNOWLEDGE:

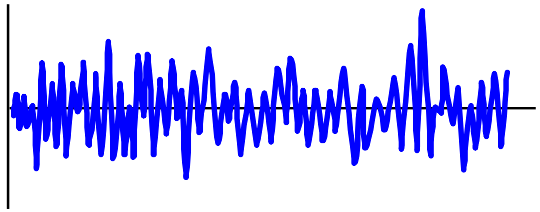
Subject:	Category			
	I	II	III	IV
1. Vibration Principles:				
Basic motion	X	X	X	
Period, frequency	X	X	X	
Amplitude (Peak, peal-to-peak, RMS)	X	X	X	
Parameters (Displacement, velocity, acceleration)	X	X	X	
Units, unit conversions	X	X	X	
Time and frequency domains	X	X	X	
Vectors, modulation			X	X
Phase		X	X	X
Natural frequency, resonance, critical speeds	X	X	X	X
Force, response, damping, stiffness			X	X
Instabilities, non-linear systems				X
2. Data Acquisition:				
Instrumentation	X	X	X	X
Dynamic range, signal to noise ratio			X	X
Transducers	X	X	X	
Sensor mounting, mounted natural frequency	X	X	X	
Fmax acquisition time		X	X	
Proximity sensor conventions		X	X	
Triggering		X	X	
Test planning		X	X	X
Test procedures	X	X	X	X
Data formats		X	X	
Computer database upload/download	X			
Recognition of poor data	X	X	X	
3. Signal Processing:				
RMS/peak detection				X
Analogue/digital conversion				X
Analogue recording and digital sampling		X	X	X
FFT computation			X	X
FFT application	X	X		
Time windows (Uniform, Hanning, flat-top)		X	X	
Filters (Low pass, high pass, band pass, tracking)		X	X	X
Anti-aliasing		X	X	X
Bandwidth, resolution		X	X	X
Noise reduction		X	X	X


Drive
Sensor
Mass Unbalance
Imposed
Motion
Follower
Rotation
Cam


Dimples in Bearings
Misalignment
Loose, Bottomed
Bolts
Cracks
Poor Grouting or
Support

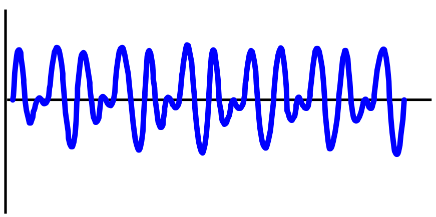
Types of Signals

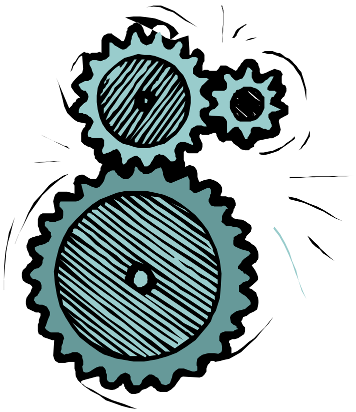
Stationary signals



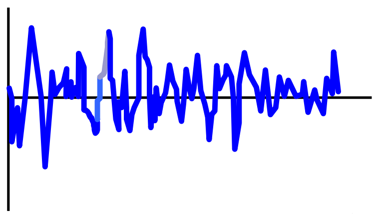
Non-stationary signals

Deterministic

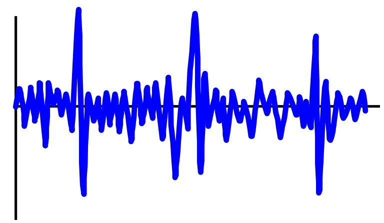




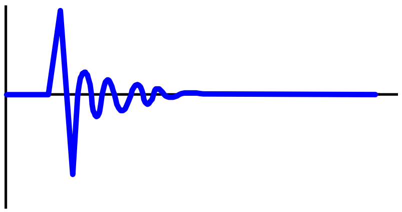
Random



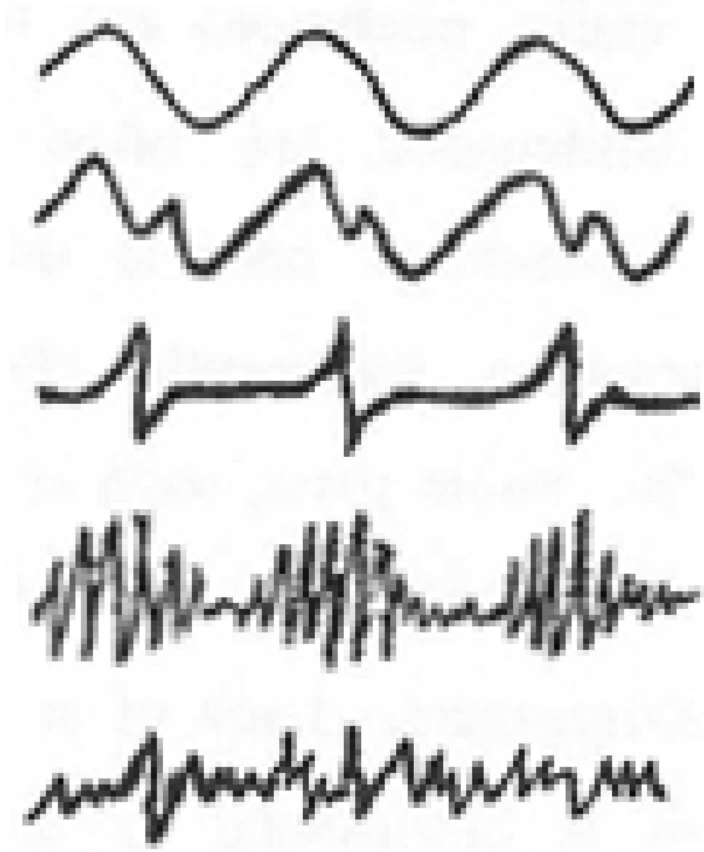
Continuous



Transient



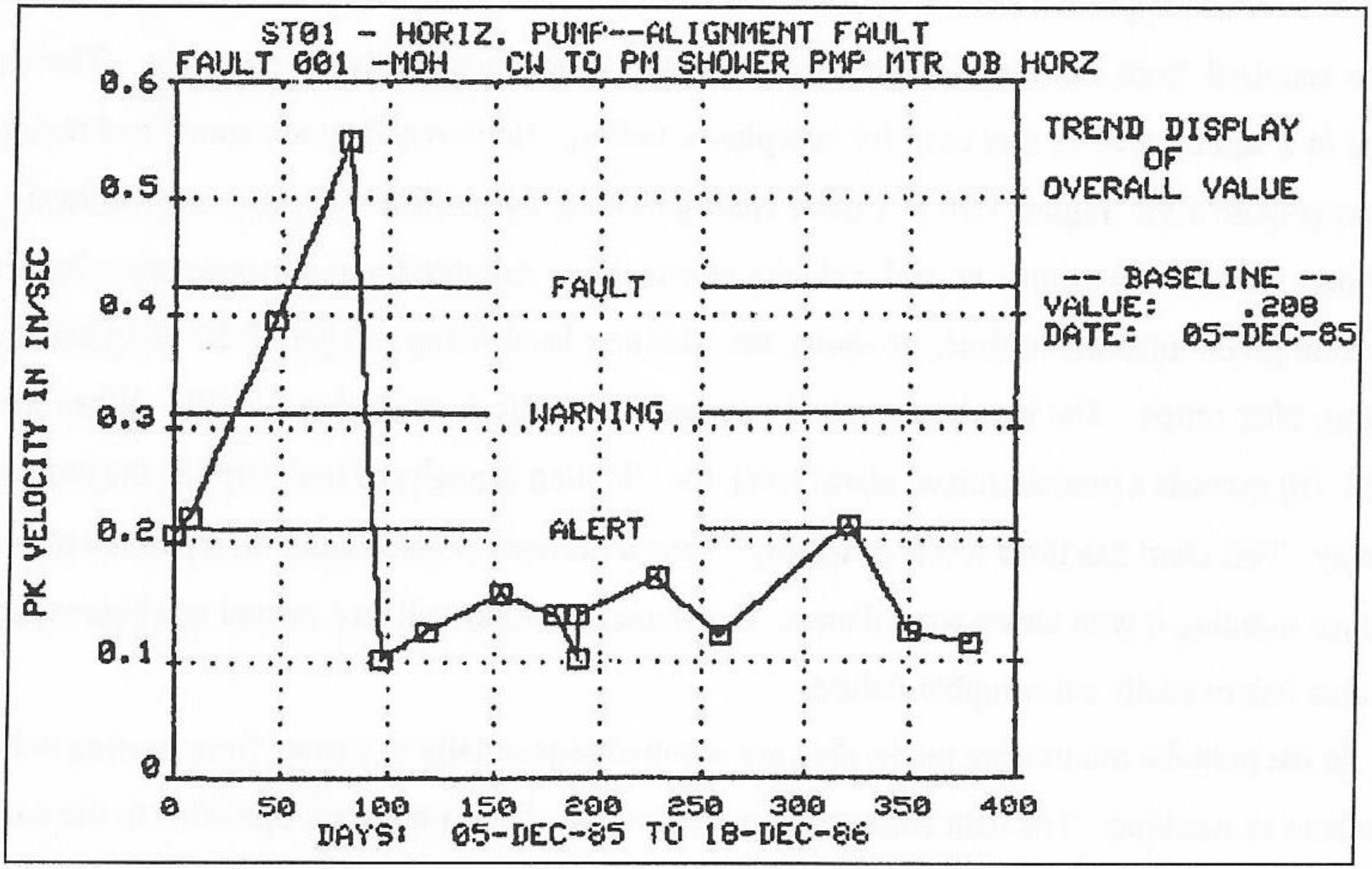
Types of Vibrations

Harmonic		Mass Unbalance
Periodic		Misalignment
Impulsive		Rolling Element Bearing, Gears tooth
Pulsating		
Random		Cavitation in Pumps

LOCATION	UNITS	DATE	PREV. VALUE	LAST VALUE	% CHANGE	ALARM STATUS
MOTOR OBD HORIZONTAL	IPS-Pk	1/23/03	0.237	0.183	-23	
MOTOR OBD VERTICAL	IPS-Pk	1/23/03	0.251	0.230	-8	
MOTOR OBD AXIAL	IPS-Pk	1/23/03	0.402	0.304	-24	A1
MOTOR IBD HORIZONTAL	IPS-Pk	1/23/03	0.223	0.168	-25	
MOTOR IBD VERTICAL	IPS-Pk	1/23/03	0.251	0.350	39	A1
MOTOR IBD AXIAL	IPS-Pk	1/23/03	0.430	0.354	-18	A1
DRIVE INPUT HORIZONTAL	IPS-Pk	1/23/03	0.320	0.206	-36	
DRIVE INPUT VERTICAL	IPS-Pk	1/23/03	0.259	0.174	-33	
DRIVE INPUT AXIAL	IPS-Pk	1/23/03	0.183	0.179	-2	
DRIVE OUTPUT HORIZONTAL	IPS-Pk	1/23/03	0.295	0.152	-14	
DRIVE OUTPUT VERTICAL	IPS-Pk	1/23/03	0.284	0.154	-46	
DRIVE OUTPUT AXIAL	IPS-Pk	1/23/03	0.212	0.136	-36	
PUMP IBD HORIZONTAL	IPS-Pk	1/23/03	0.190	0.168	-12	
PUMP IBD VERTICAL	IPS-Pk	1/23/03	0.174	0.175	1	
PUMP IBD AXIAL	IPS-Pk	1/23/03	0.110	0.093	-15	
PUMP OBD HORIZONTAL	IPS-Pk	1/23/03	0.230	0.202	-12	
PUMP OBD VERTICAL	IPS-Pk	1/23/03	0.124	0.140	13	
PUMP OBD AXIAL	IPS-Pk	1/23/03	0.113	0.060	-47	
MOTOR OBD VERTICAL	Mils-Pk-Pk	1/23/03	1.03	0.80	-22	
MOTOR OBD HORIZONTAL	Mils-Pk-Pk	1/23/03	1.43	1.42	-1	
MOTOR IBD VERTICAL	Mils-Pk-Pk	1/23/03	2.00	1.54	-23	
MOTOR IBD HORIZONTAL	Mils-Pk-Pk	1/23/03	2.50	1.32	-47	
DRIVE INPUT VERTICAL	Mils-Pk-Pk	1/23/03	2.97	3.10	4	A1
DRIVE INPUT HORIZONTAL	Mils-Pk-Pk	1/23/03	2.80	3.66	31	A1
DRIVE OUTPUT VERTICAL	Mils-Pk-Pk	1/23/03	2.57	1.70	-34	
DRIVE OUTPUT HORIZONTAL	Mils-Pk-Pk	1/23/03	2.57	2.10	-18	
PUMP IBD VERTICAL	Mils-Pk-Pk	1/23/03	1.09	0.85	-22	
PUMP IBD HORIZONTAL	Mils-Pk-Pk	1/23/03	1.42	1.14	-20	
PUMP OBD VERTICAL	Mils-Pk-Pk	1/23/03	0.23	0.23	0	
PUMP OBD HORIZONTAL	Mils-Pk-Pk	1/23/03	0.49	0.63	29	

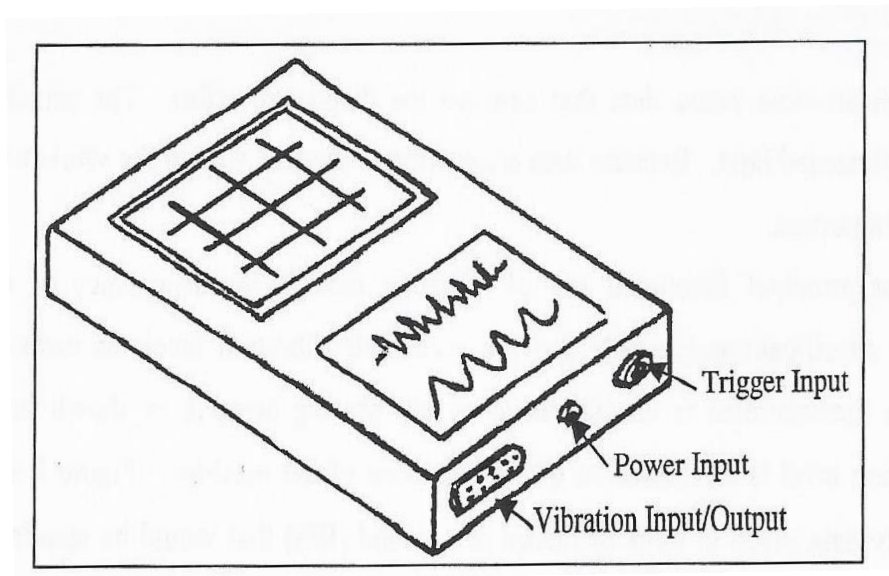
Figure 6.1. Example of a Route for Motor Driven Boiler Feed Pump

Vibration



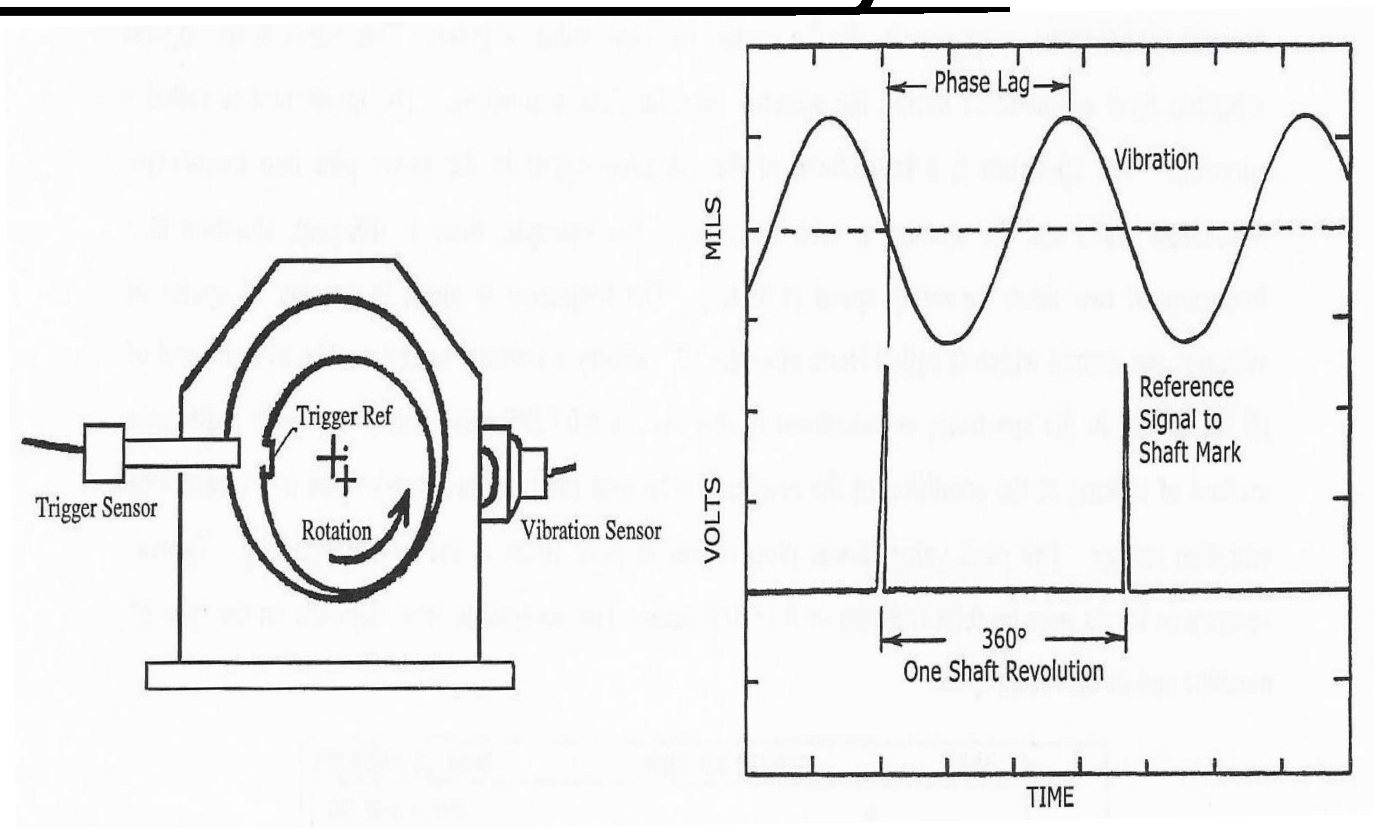
Monthly Trend Plot of a Pump Motor for Peak Velocity.

Measurement and Analysis



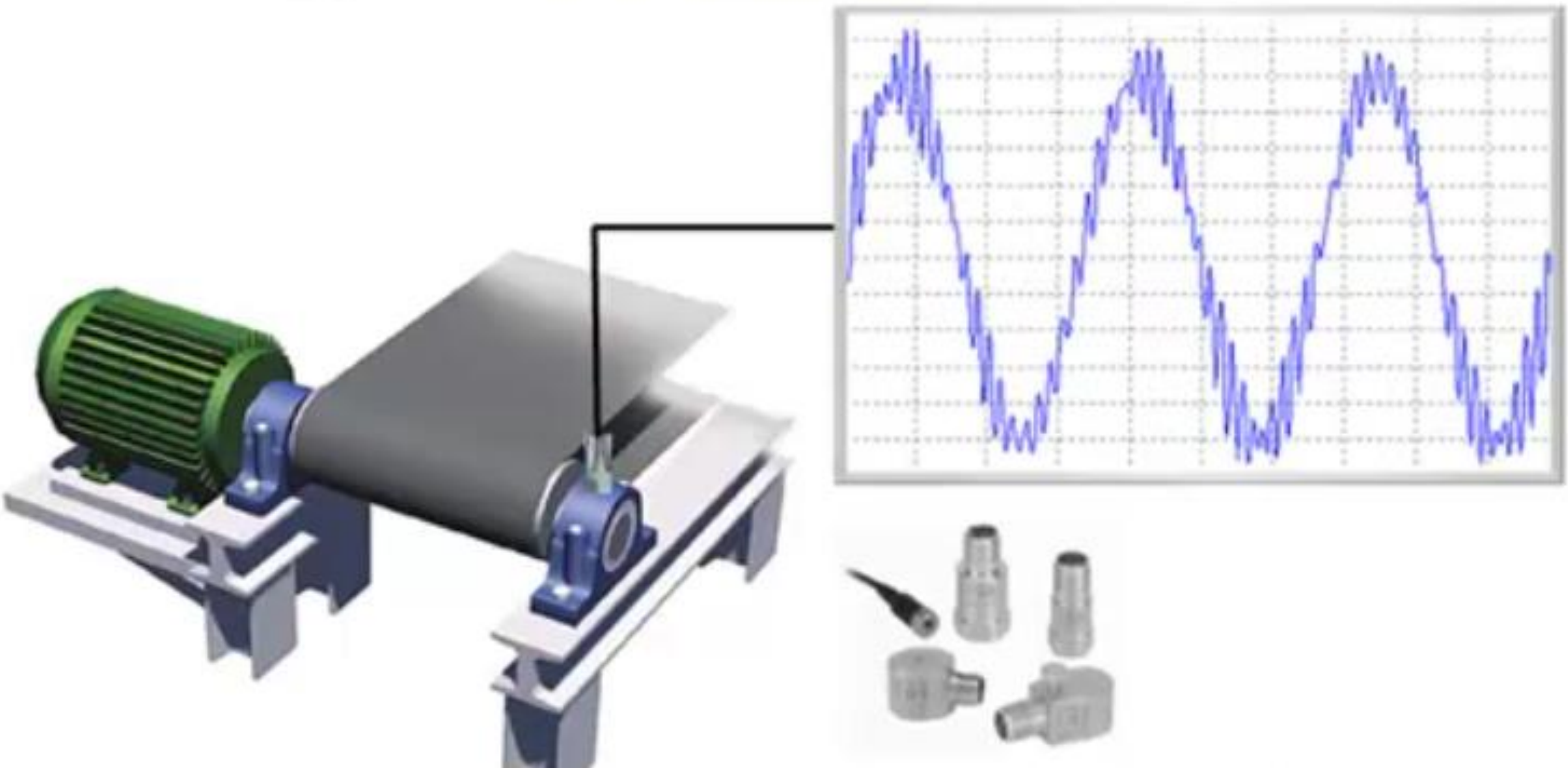
Schematic of Data Collection Instrument.

Measurement and Analysis

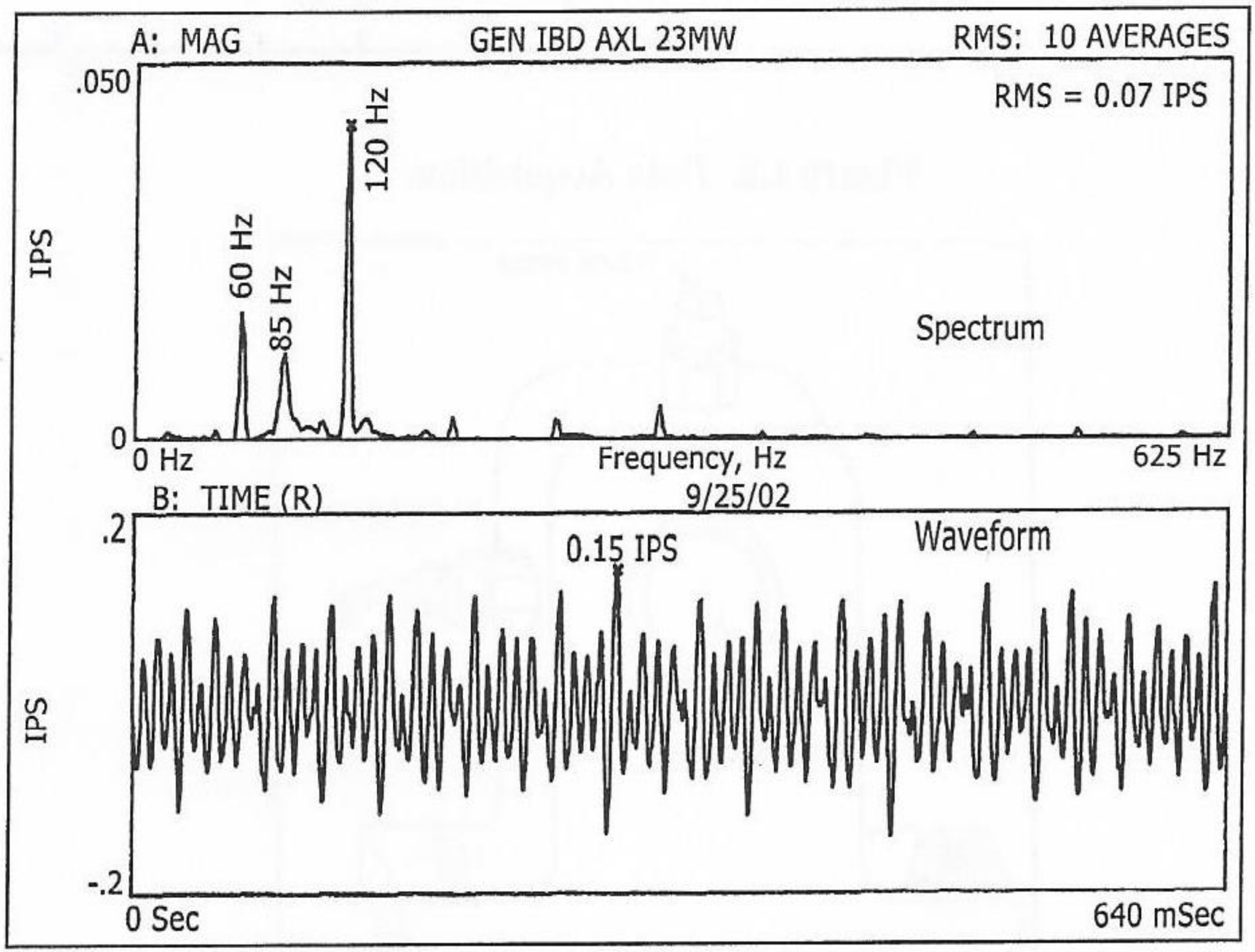


Data Acquisition

Measurement and Analysis



Measurement and Analysis



PHYSICAL OBSERVATIONS by Human Senses

While there are several types of recorded data that form the basis for machine fault and condition analysis, among the most basic data are direct observations by the person doing the data collection based on human senses - hearing, sight, touch, smell, and taste. Human sensory capabilities, although not analytical, cannot be underestimated in the machine analysis process.

Noise

Unusual noises can indicate rubs, bearing defects, looseness, improper assembly, lack of lubrication, and any other metal to metal contact problems. A listening rod or screw driver can be used to detect a bearing defect or rubbing in a low speed machine. In pumps, a sign of flow problems is a noise that sounds like gravel in the piping. Motors and generators may emit high frequency whining noises when they are subject to excessive vibration due to casing distortion, misalignment, or coupling unbalance.

Noise

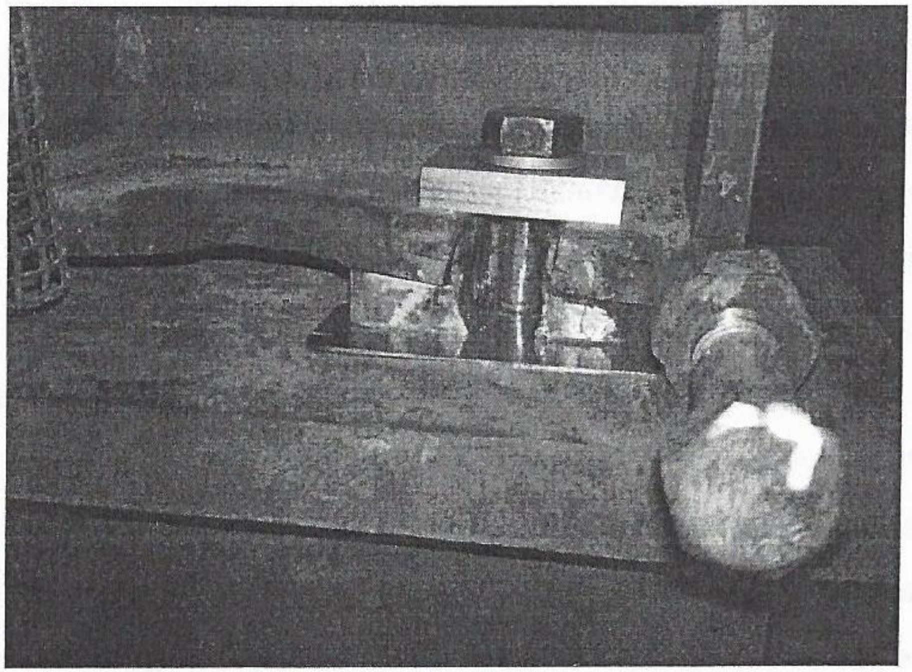
High pitched noise from new gears indicates bad construction and machinery quality or design (low contact ratio). Rubbing of guards by pulleys and belts will cause impacting and noise. Lack of lubrication in oil starved bearings or bearings with excessive clearance means that the bearing needs attention. Excessive noise is almost always an indicator of trouble. The experienced data collector will be able to enhance their analytical capability by learning to identify noise sources and associate the physical problem with them.

Sight

The use of sight is an even more powerful tool for data collectors. Smoke, fire, and catastrophic failures need and get immediate attention. However, other mundane faults may go unnoticed for months. Foundation and bearing pedestal faults are the source of many cases of excessive vibration.
A flashlight and feeler gage or knife help to root out these type problems. Squishing oil between joints is a certain clue of looseness.
Cracks in ducting and piping and other machine components provide clues to the presence of excessive vibration. Vibration analysis will confirm these faults

Sight

Vibration analysis will confirm these faults. The data collector may have to go off route to measure these cases.



Hammered and Torched to Fit.

Smell and Touch

The senses of smell and touch are less important but should not be neglected. Unusual, abnormal odors are easily detected by the human sense of smell. Oil smoke can be smelled long before an oil fire. Ammonia and other chemical and gas leaks are best detected by the nose. Even small quantities can be detected. Hot bearings or other machine parts that are not normally operating above ambient temperature can be identified by touch. However, the data collector needs to exercise extreme caution. A steaming or red hot machine should not be touched. The water can confirm the temperatures are above 100º C.

The use of taste is not recommended in this work.

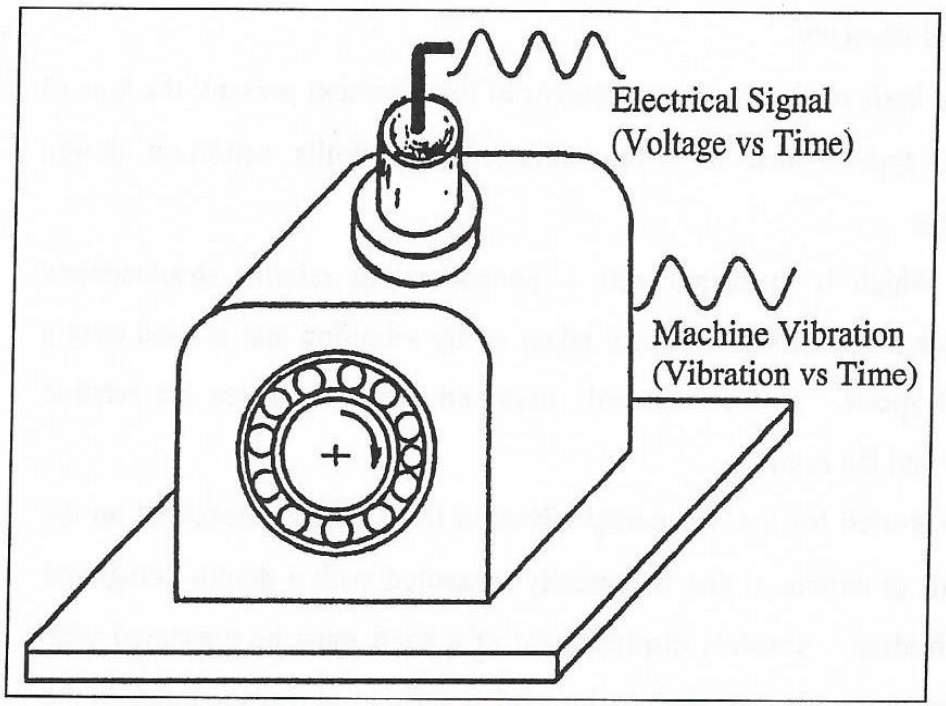
PERIODIC AND CONTINUOUS DATA COLLECTION

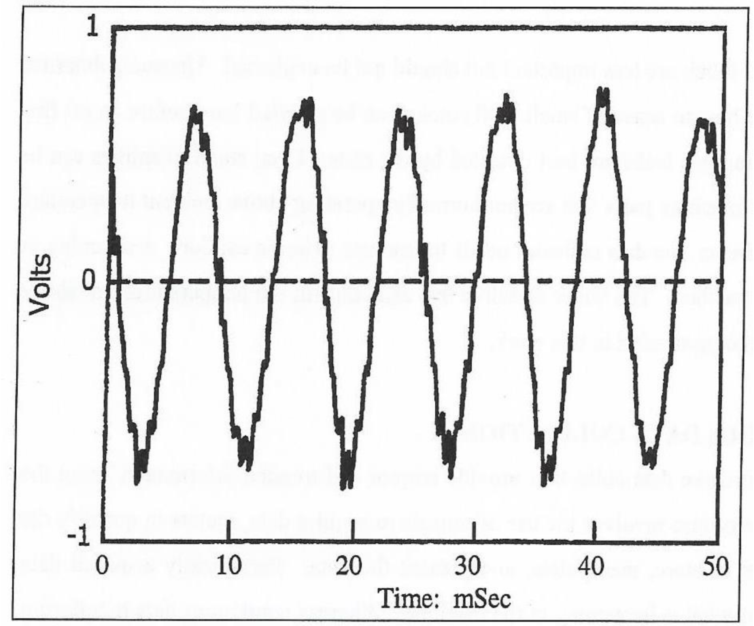
Periodic and continuous non-intrusive data collection provide current and trended information about the condition of a machine. The procedure involves the use of sensors to acquire data, meters to quantify the measured data, and instruments to store, manipulate, and present the data. Periodically acquired data provide an intermittent record of what is happening in the machine. Whereas continuous data monitoring and collection provides continuous surveillance along with the ability to protect the machine through data based automatic shutdown.

PERIODIC AND CONTINUOUS DATA COLLECTION

Measurement of vibration for analytical use is performed by a sensor, sometimes called a transducer or pickup, and is nonintrusive to the machine or process. The sensor transforms the vibration (mechanical motion) of the mounting location to an electrical voltage which varies with time.

PERIODIC AND CONTINUOUS DATA COLLECTION





Selecting a Measure

A measure is a unit or measures of vibration are standard of measurement that provides a means for physical evaluation. Examples of measures are pounds for weight and feet for height. Three basic available displacement, velocity, and acceleration. Ideally the sensor would directly provide the selected measure. Unfortunately, sensor limitations do not always allow direct measurement of vibration in the proper measure. Other predictive maintenance based measures are temperature, pressure, and viscosity.

Selecting a Measure

The measure is selected on the basis of the frequency content of the vibration present, the type of sensor, the design of the machine, the type of analysis to be conducted (e.g., faults, condition, design information), and the information sought.

Selecting a Measure

Relative shaft displacement

which is measured with a noncontacting relative displacement sensor, proximity probe, shows the extent of bearing clearance taken up by vibration and is used over a frequency range as wide as the shaft speed. This permanently mounted probe measures the relative motion between the point of mounting and the rotor.

Selecting a Measure

Absolute displacement

which is used for low-frequency vibration (0 to 10Hz) measured on the bearing pedestal, relates to stress (shaft or structure) and is typically measured with a double integrated accelerometer. It is called seismic vibration. Absolute displacement of a shaft must be measured with either a contacting sensor or a noncontacting sensor in combination with a seismic sensor mounted on the bearing pedestal.

Selecting a Measure

Velocity

For general machinery monitoring and analysis in the span from 10 Hz to 1,000 Hz, velocity is the default measure. Velocity as a time rate of change of displacement is dependent upon both frequency and displacement and related to fatigue. It has been shown to be a good measure in the span for 10Hz to 1,000 Hz because a single value for rms or peak velocity can be used in rough assessments of condition without the need to consider frequency. Most modem data collectors use accelerometers but the signal must be integrated to obtain velocity.

Selecting a Measure

Acceleration

is the measure used above 1,000 Hz; it relates to force and is used for such high- frequency vibrations as gearmesh and rolling element bearing defects. Acceleration and velocity are absolute measures taken on the bearing housing or as close to the bearing as possible.

Selecting a Measure

Measure	Useful Frequency Span	Physical Parameter	Application
Relative displacement (Proximity probe)	0 – 1000 HZ	stress/motion	relative motions in bearings/casings.
Absolute displacement (seismic)	0 – 10 Hz	stress/motion	machine condition
Velocity (seismic)	10 – 1000 Hz	energy/fatigue	general machine, medium-frequency vibrations
Acceleration (seismic)	>1000 Hz	force	general machine, medium-high-frequency vibrations

Selecting a Measure

The rule of thumb for measure selection is that velocity is used for bearing pedestal measurement up to 1,000 RPM and acceleration is used above that machine speed. If the machine has permanent non-contacting displacement sensors, then displacement is acquired.

Selecting a Measure

FREQUENCIES
Bearing Frequencies

$$\mathrm{FTF} = \left(\frac{\Omega}{2}\right)\left[1 - \left(\frac{\mathrm{B}}{\mathrm{P}}\right)\cos \mathrm{CA}\right]$$

$$\mathrm{BPFI} = \left(\frac{\mathrm{N}}{2}\right)\Omega\left[1 + \left(\frac{\mathrm{B}}{\mathrm{P}}\right)\cos \mathrm{CA}\right]$$

$$\mathrm{BPFO} = \left(\frac{\mathrm{N}}{2}\right)\Omega\left[1 - \left(\frac{\mathrm{B}}{\mathrm{P}}\right)\cos \mathrm{CA}\right]$$

$$\mathrm{BSF} = \left(\frac{\mathrm{P}}{2\mathrm{B}}\right)\Omega\left[1 - \left(\frac{\mathrm{B}}{\mathrm{P}}\right)^2 \cos^2 \mathrm{CA}\right]$$

FTF = fundamental train frequency
BPFI = ball pass frequency, inner race
BPFO = ball pass frequency, outer race
BSF = ball spin frequency
RPM = shaft speed
B = ball or roller diameter, in

CA = contact angle
Ω = machine speed
N = number of rolling elements
P = pitch diameter, in

Bearing defect frequencies are same units as machine speed

Selecting a Measure

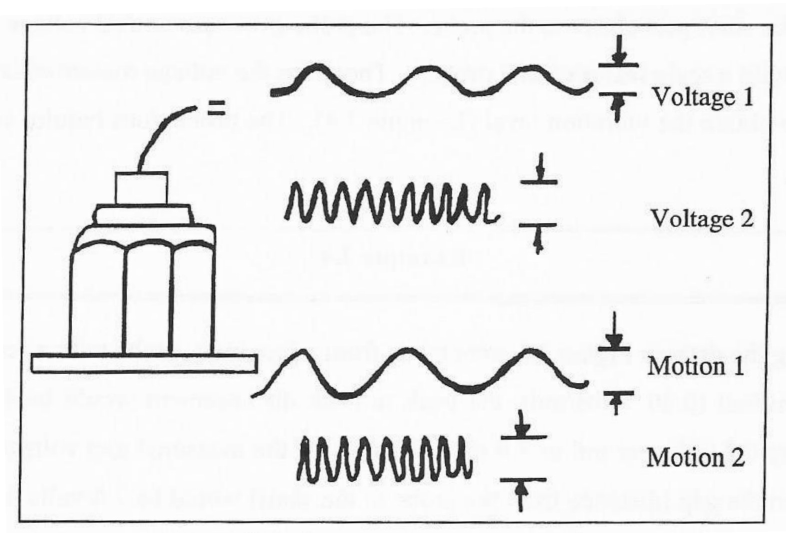
FREQUENCIES

FAN

blade pass frequency = no blades x RPM

Vibration Sensors

Magnitude, frequency, and phase between two signals are used for evaluation. Sensor selection is based on sensitivity, size required, selected measure, frequency response, and machine design and speed. The sensor should be mounted as close to the source of vibration as possible.



Vibration Sensors

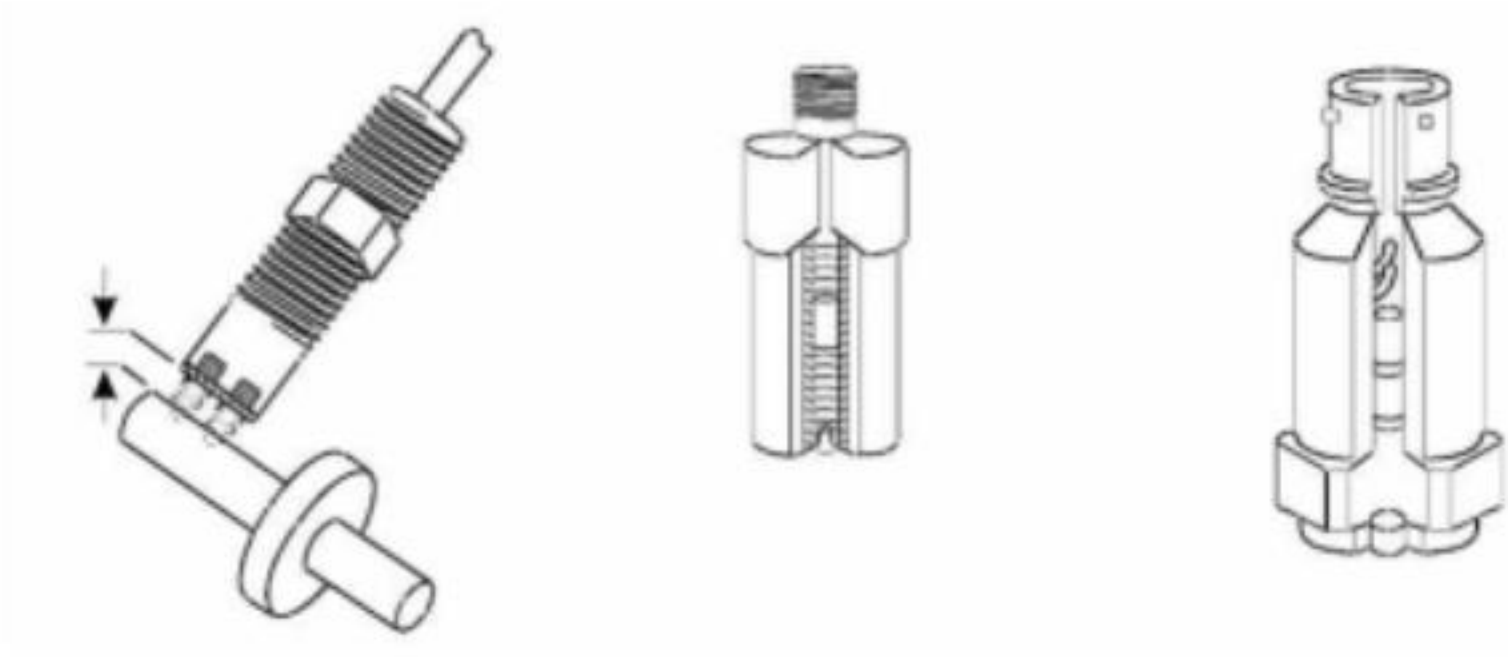
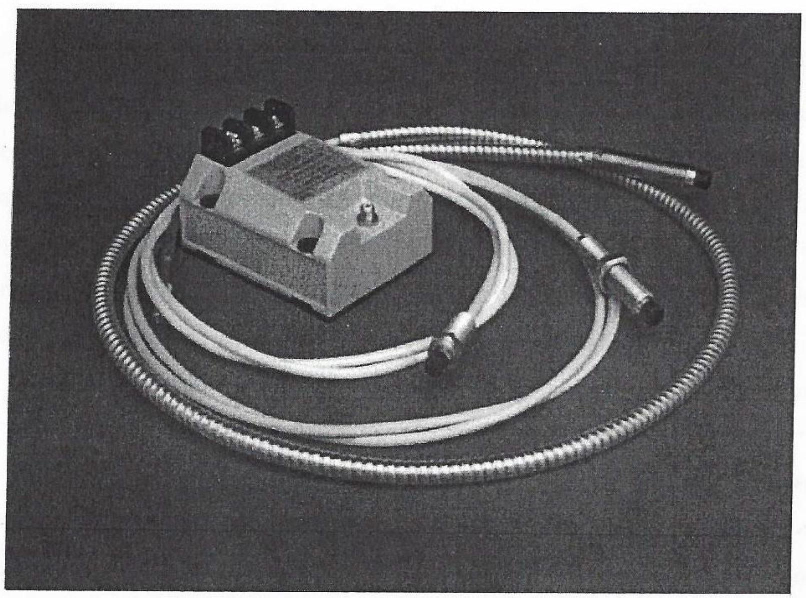


Figure 4-4 A proximity probe, a velocimeter, and an accelerometer.

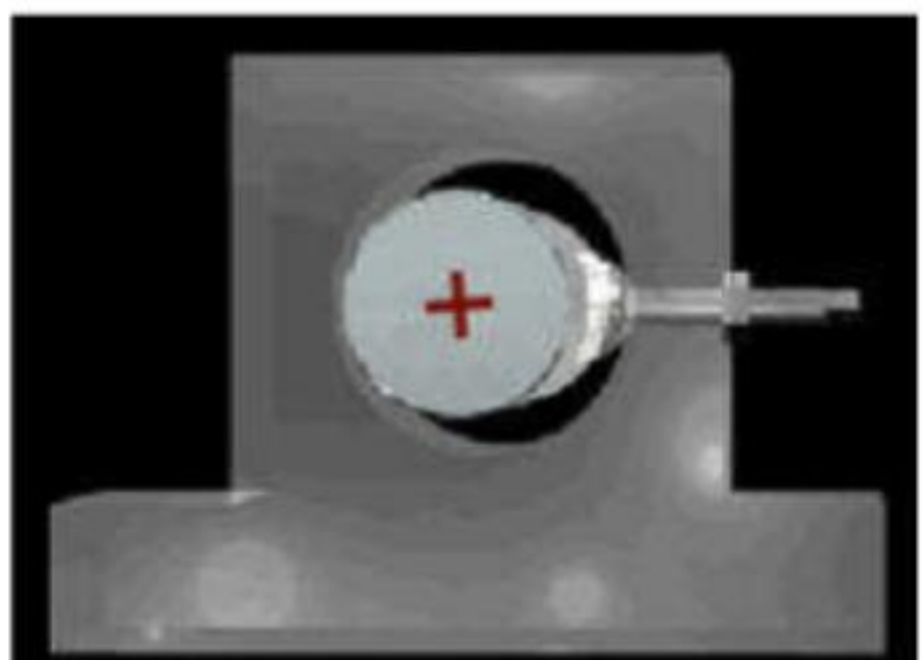
Proximity probes

The proximity probe (non-contacting eddy current displacement transducer) shown in Figure 3.5 measures static and dynamic displacement of a shaft relative to the bearing housing. It is permanently mounted on many large (greater than 1,000 HP) machines for monitoring (protection and trending) and analysis.



Proximity probes

The probe generates a negative DC voltage proportional to the distance of the shaft from the sensor (gap). The typical gap is 40 mils or at 200 mv/mil, 8 volts. The negative voltage decreases as the shaft gets closer to the probe. The probe generates an AC voltage proportional to the vibration with a scale factor of 200 mv/mil. Therefore, the voltage measured is divided by the scale factor to obtain th
3.4). The probe does requi
supply.



Proximity Probe

Figure 4-7 Eddy current probes have 3 components: the probe, a driver, and the cable between them.

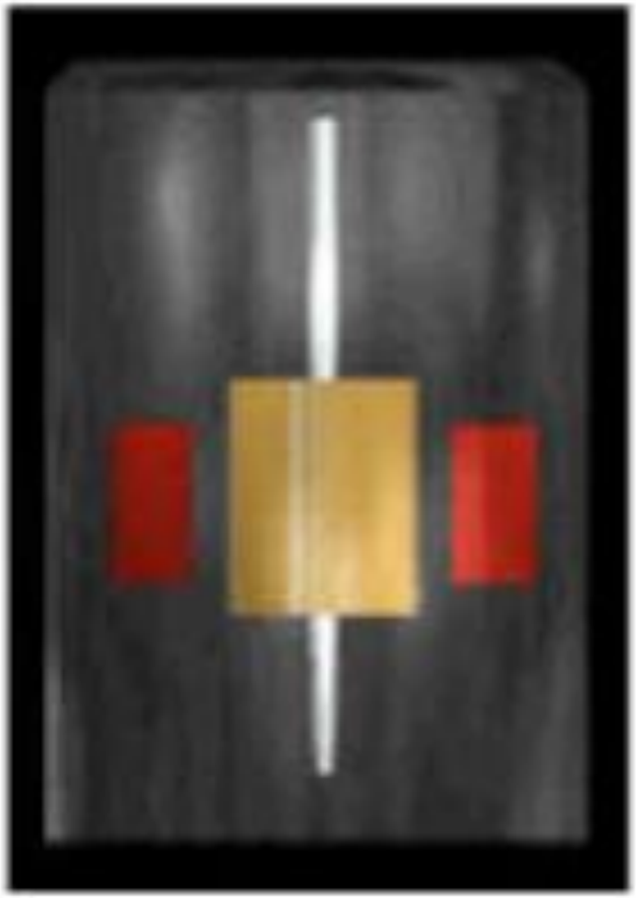
Example 3.4

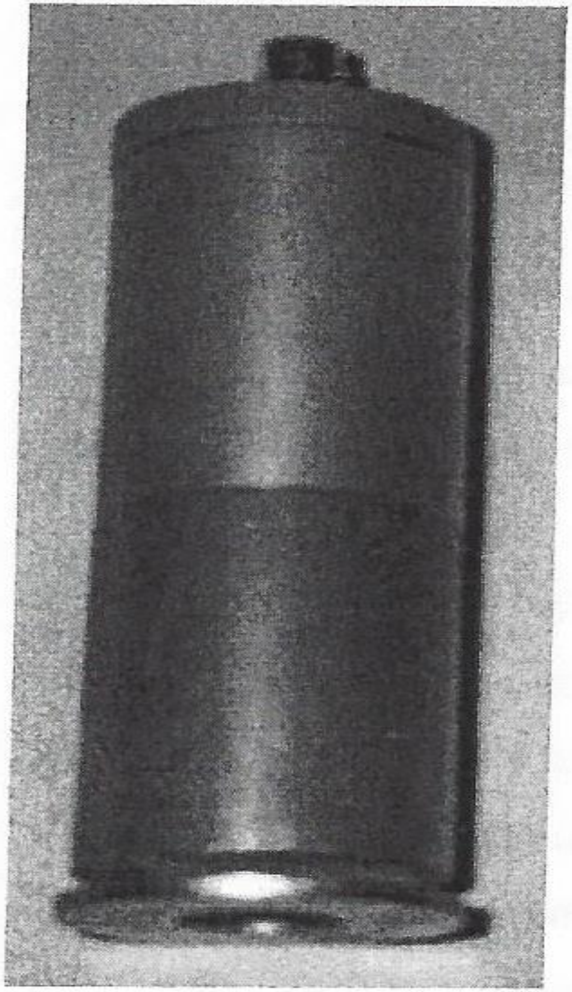
Assuming the data on Figure 3.3 were taken from a proximity probe with a scale factor of 200 mv/mm (0.20 Volts/mm), the peak to peak displacement would be 1.58 volts divided by 0.2 volts per mm or 7.9 mm-pk to pk. If the measured gap voltage was 7.6 volts, then the gap (distance from the probe to the shaft) would be 7.6 volts divided by 0.2 Volts/mm or 38 mm.

Velocity transducers

Velocity transducers. The velocity transducer is a seismic transducer (i.e., it measures absolute vibration) that is used to measure vibration levels on casings or bearing housings in the range from 10 Hz to 2,000 Hz. The transducer is self-excited - that is, it requires no power supply. The self-generated signal can be directly passed to an oscilloscope, meter, or analyzer for evaluation. A typical velocity transducer generates 500 mv/(in./sec).

Velocity transducers





Accelerometers

Accelerometers are used to measure vibration levels on casings and bearing housings; they are the transducers typically supplied with electronic data collectors. An accelerometer (Figure 3.7) consists of a small mass mounted on a piezoelectric crystal that produces an electrical output proportional to acceleration when a force is applied from the vibrating mass.

Accelerometers

Figure 4-12 Accelerometers are typically mounted on a bearing housing via magnet


Accelerometers

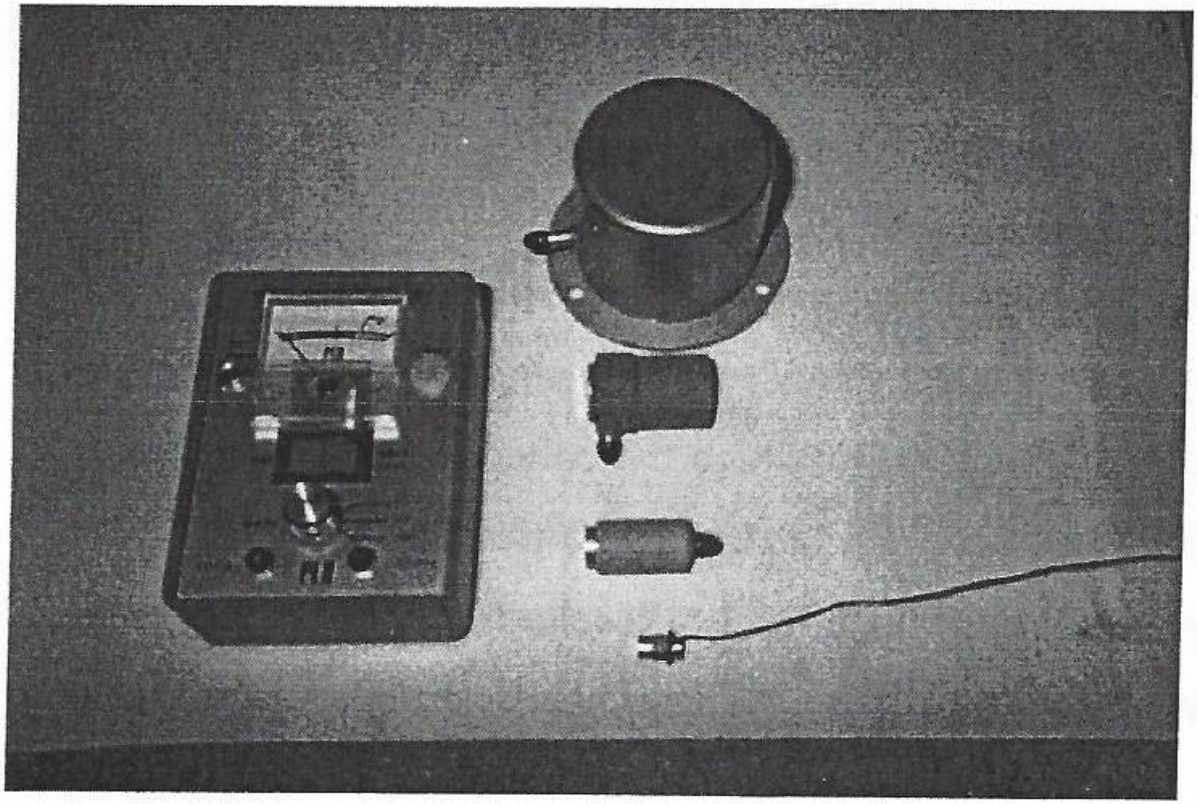
Accelerometers

Figure 4-15 Triaxial accelerometers have 3 accelerometers in one unit

Accelerometers

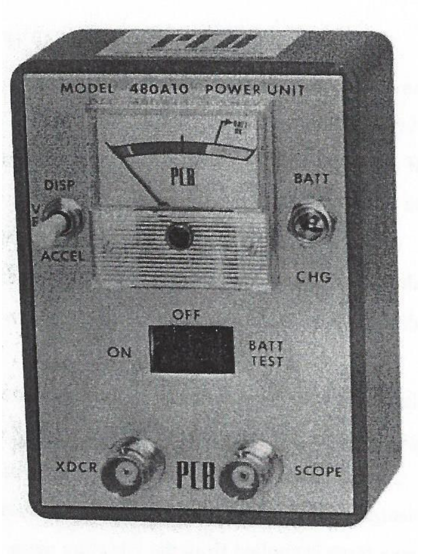
The size of an accelerometer is proportional to its sensitivity. Small accelerometers (the size of a pencil eraser) have a sensitivity of 5 mv/g (1 g = 386.1 in./sec2) and a flat frequency response to 25 kHz. A 1,000 mv/g accelerometer, which is used for low-frequency measurement, may be as large as a velocity sensor; however, the limit of its usable frequency span may be to 1,000 Hz. The analyst should be aware of the properties of each accelerometer being used.

Accelerometers



Accelerometers

If vibration velocity is desired, the signal is usually integrated, which electronically converts acceleration to velocity, before it is recorded or analyzed; an analog integrator/power supply is shown in Figure 3.8.



Analog Integrator and Power

Accelerometers

Accelerometers are recommended for permanent seismic monitoring because of their extended life and because their cross sensitivity is low. (Cross sensitivity means that the transducer generates a signal in horizontal direction from vibration in the vertical direction.)
However, cable noise, transmission distance, and temperature sensitivity of the accelerometer must be carefully evaluated. Excellent guidelines are available from vendors for accelerometer use.

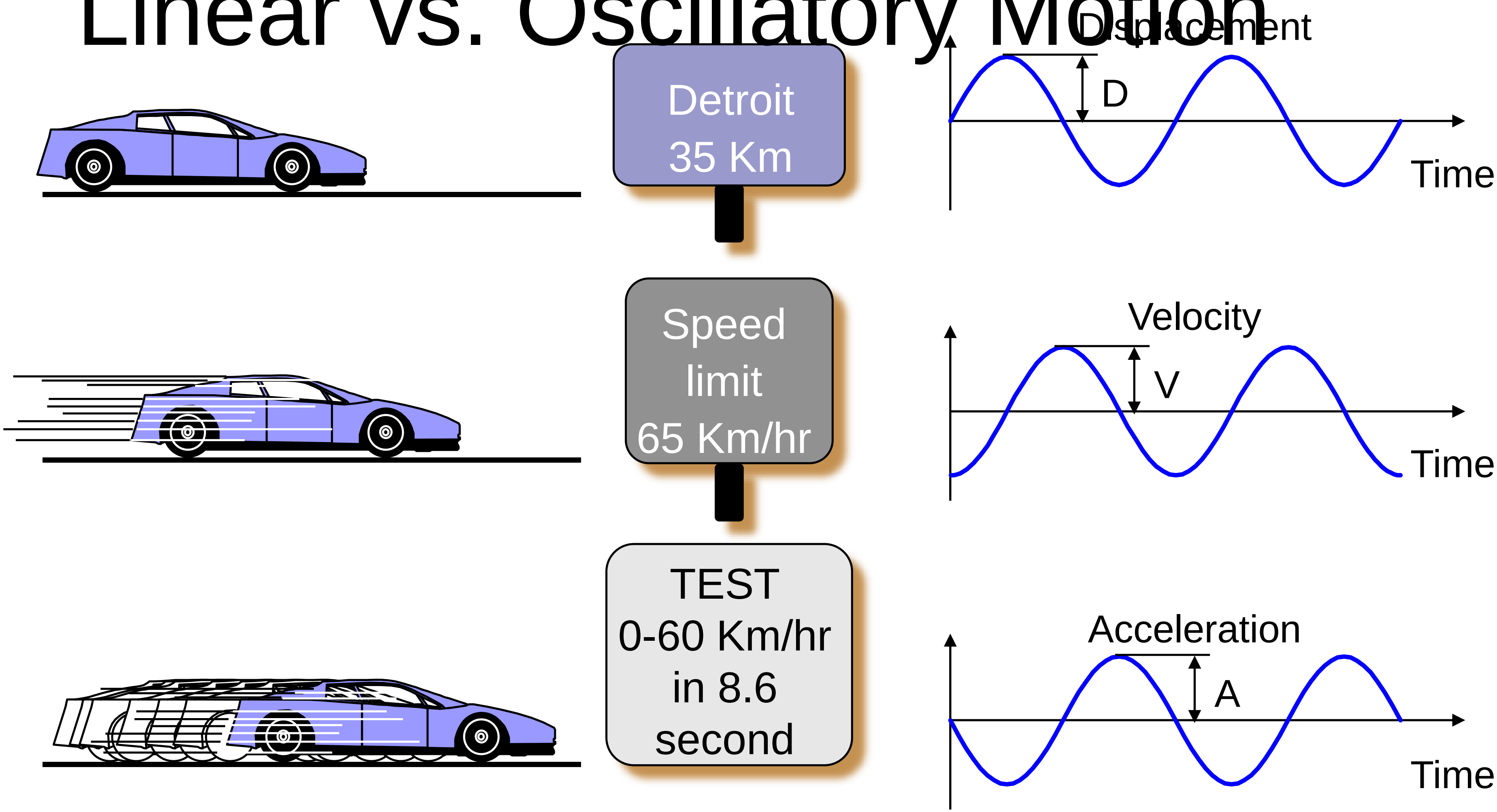
Sensor Selection

Important considerations in sensor selection include frequency response, signal-to-noise ratio, size, thermal and amplitude sensitivity of the sensor, and the strength of the signal being measured. The frequency range of the sensor must be compatible with the frequencies generated by the mechanical components of the machine. Otherwise, another transducer must be selected and the signal converted to the proper measure. For example, if the velocity measure is desired at frequencies above 2,000 Hz, an accelerometer integrated to velocity should be selected to obtain the signal. If the time waveform of the velocity measure is desired, the signal must be acquired from a velocity pickup or analog integrated signal from an accelerometer, either within or external to the data collector.

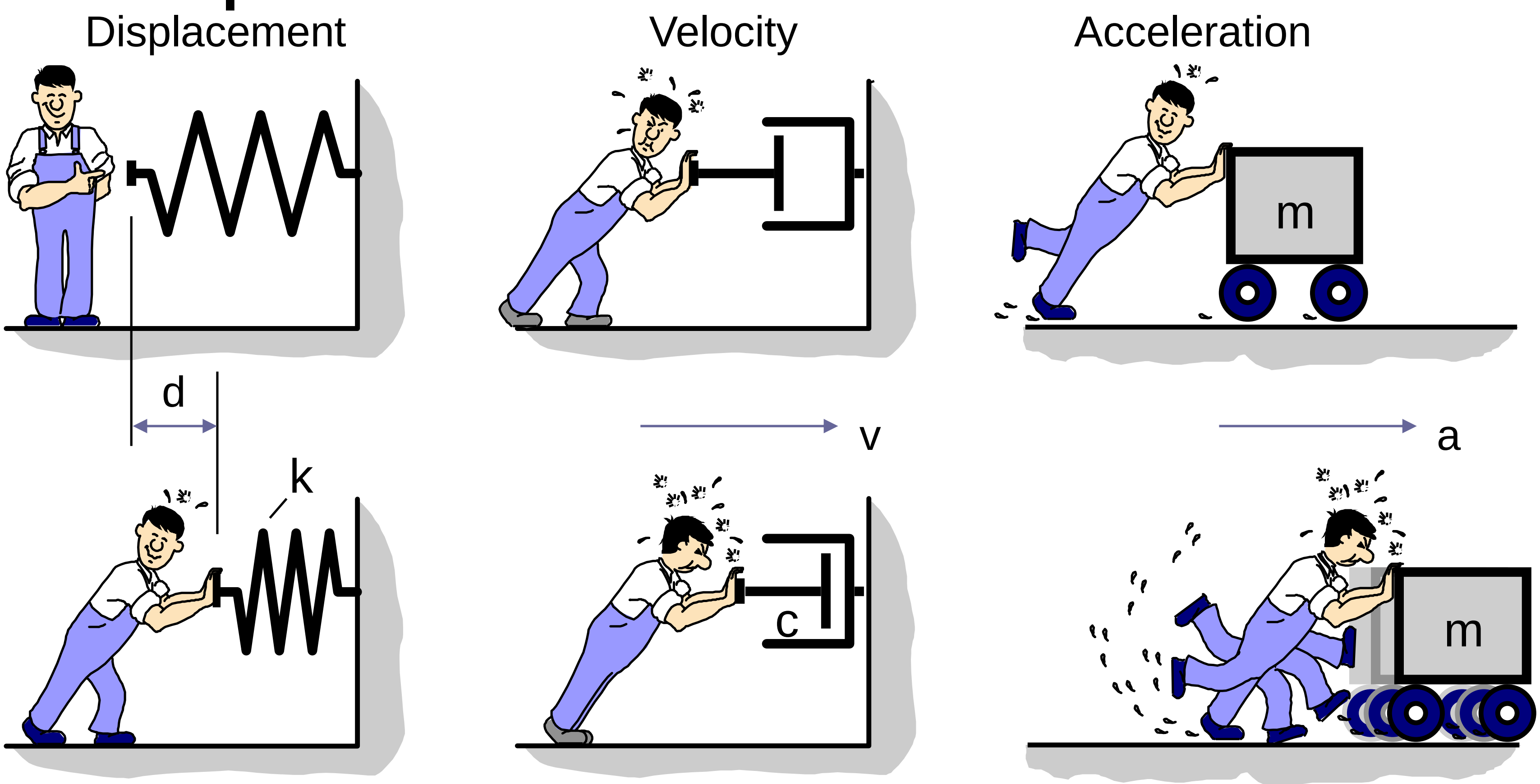
Sensor Selection

The cable that transmits the signal to the data collector can cause erroneous readings. Many standard cables are specially wound cords that are more convenient than the standard coaxial construction. But, because many conductors are flexible at the core, individual strands may fail at stress points as a result of handling or packing in a carrying case. In addition, the terminals must be handled carefully.

Linear vs. Oscillatory Motion



Mechanical Parameters and Components

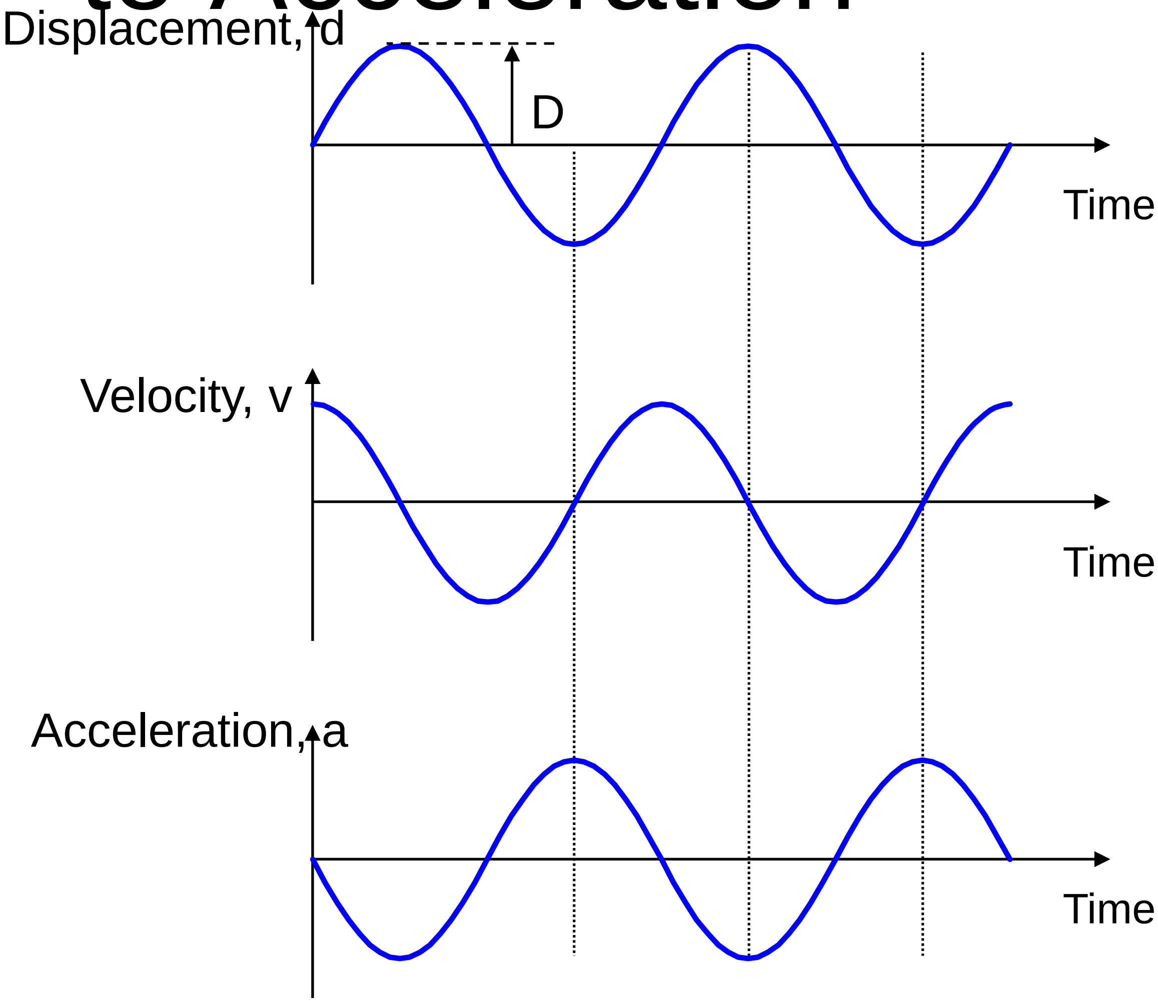


$F = k \times d$

$F = c \times v$

$F = m \times a$

Conversion from Displacement to Acceleration



$$d = D \sin \omega t$$

$$\boxed{d = D}$$

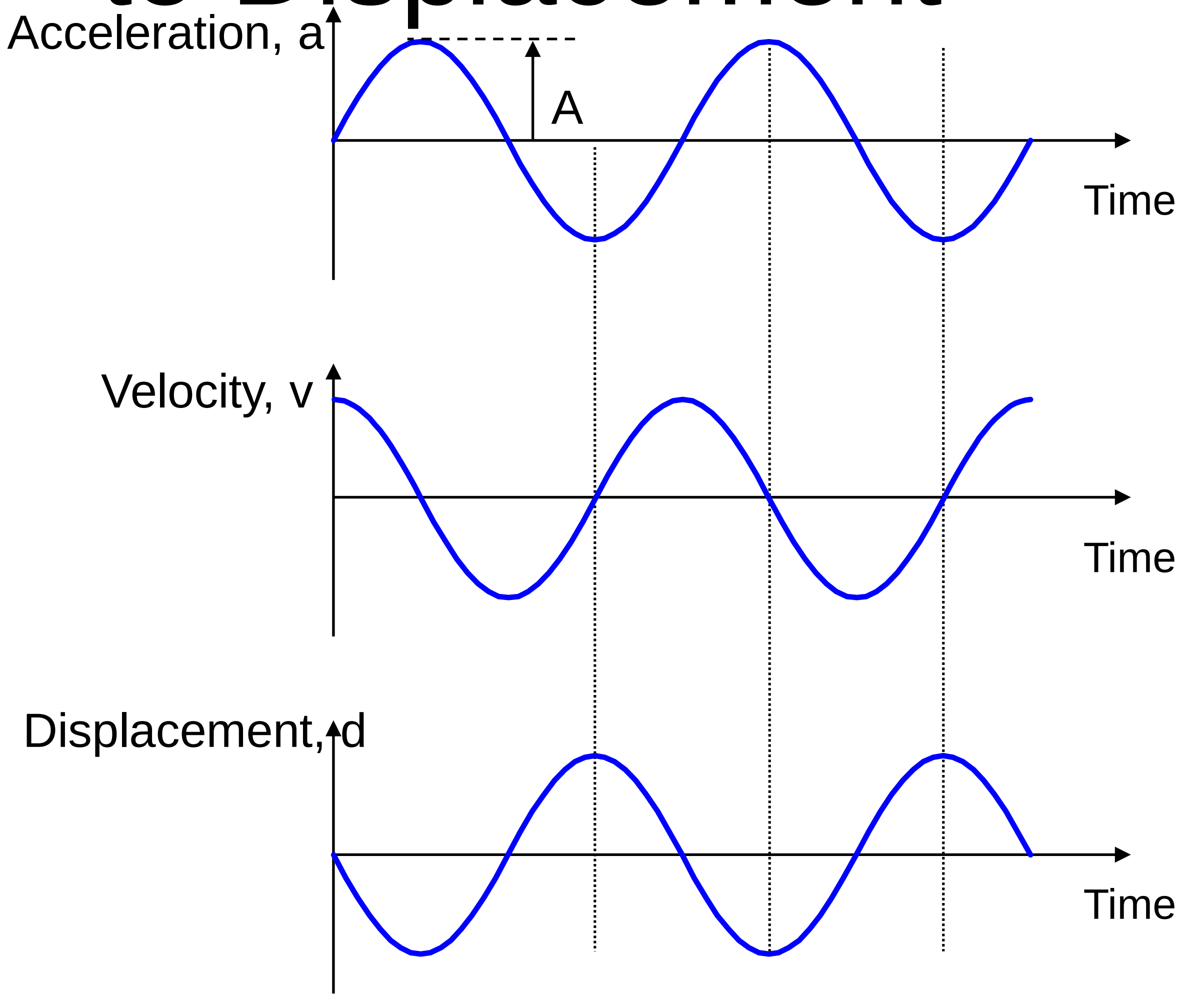
$$v = \frac{dd}{dt} = D\omega \cos \omega t$$

$$\boxed{v = D\omega = D2\pi f}$$

$$a = \frac{d^2d}{dt^2} = D\omega^2 \sin \omega t$$

$$\boxed{a = D\omega^2 = D4\pi^2 f^{\,2}}$$

Conversion from Acceleration to Displacement



$a = A \sin \omega t$

$\boxed{a = A}$

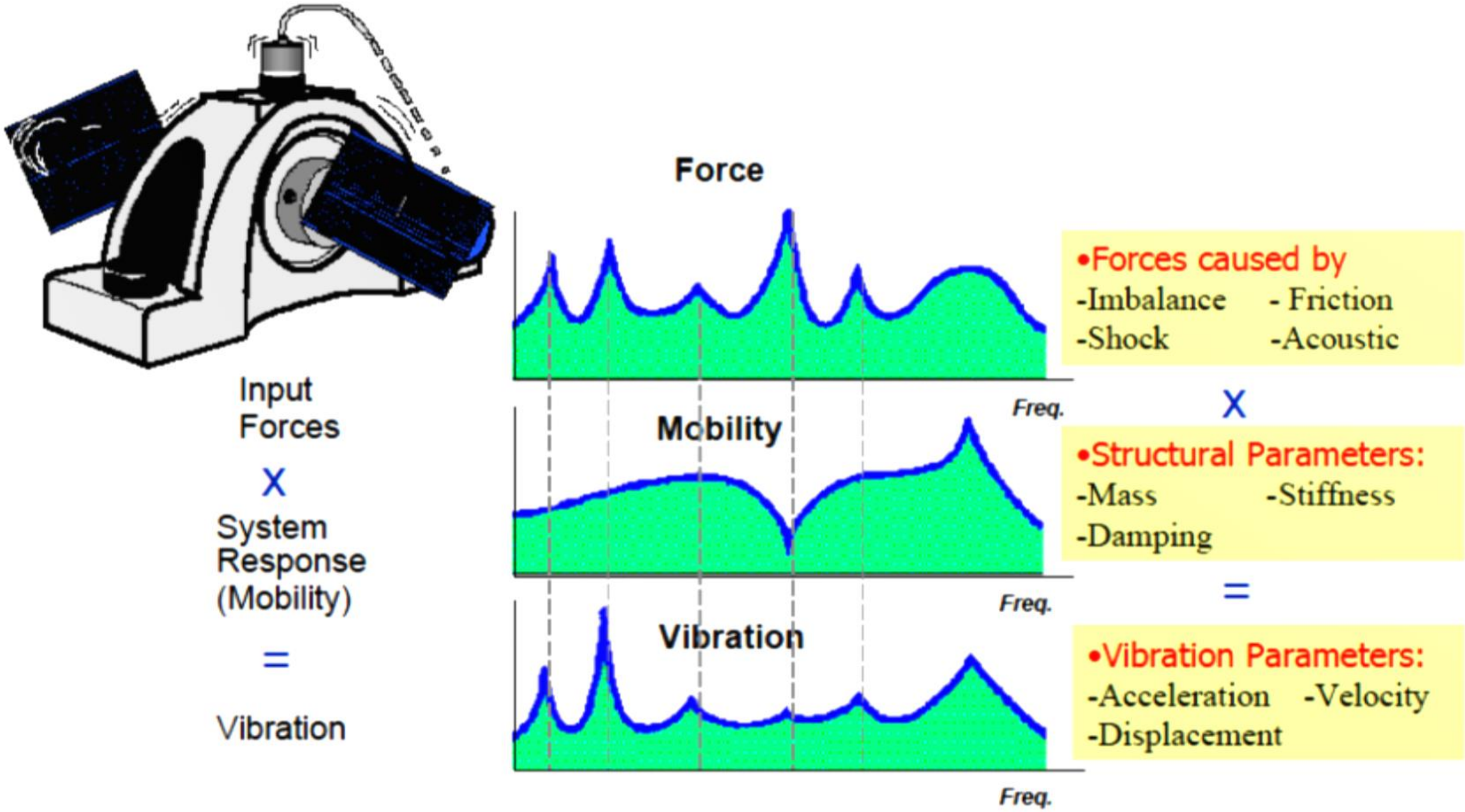
$v = \int a\,dt = -\dfrac{A}{\omega} \cos \omega t$

$\boxed{v = \dfrac{A}{\omega} = \dfrac{A}{2\pi f}}$

$d = \int\int a\,dt\,dt = -\dfrac{A}{\omega^2} \sin \omega t$

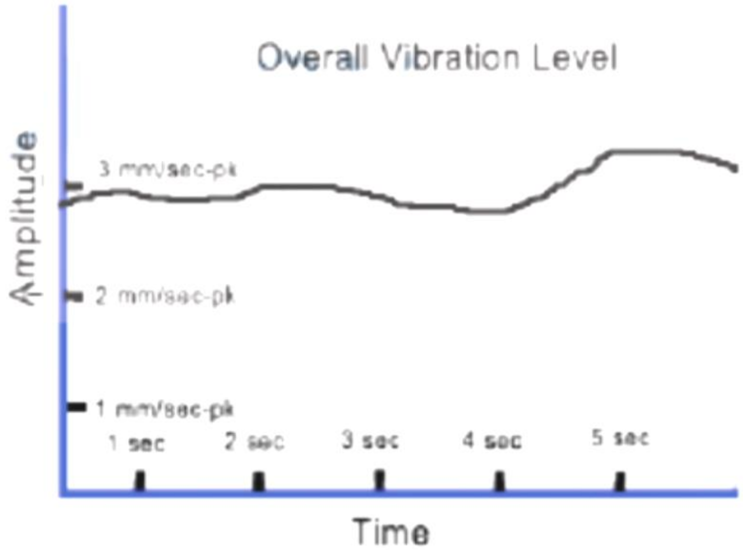
$\boxed{d = \dfrac{A}{\omega^2} = \dfrac{A}{4\pi^2 f^2}}$

What is Vibration



Overall Amplitude

- It is the total vibration amplitude over a wide range of frequencies.
- Acceleration, Velocity, or Displacement.



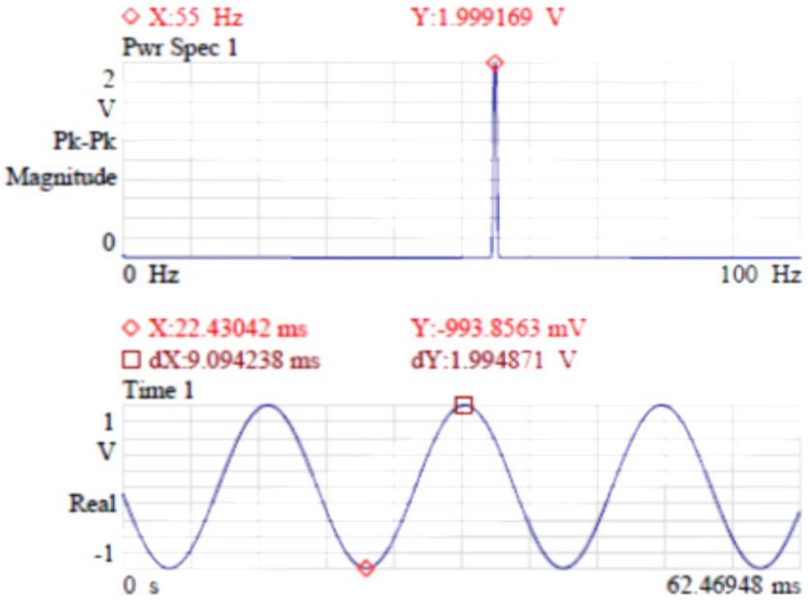
Vibration Terminology

- Displacement [peak-peak]
- Velocity [peak]
- Velocity [rms]
  - Velocity rms tends to provide the energy content in the vibration, whereas the Velocity peak depicts more of the intensity of vibration.
- Acceleration - peak

Pk-Pk (Peak - Peak)

The Peak - Peak value is expressed from the peak to peak amplitude.

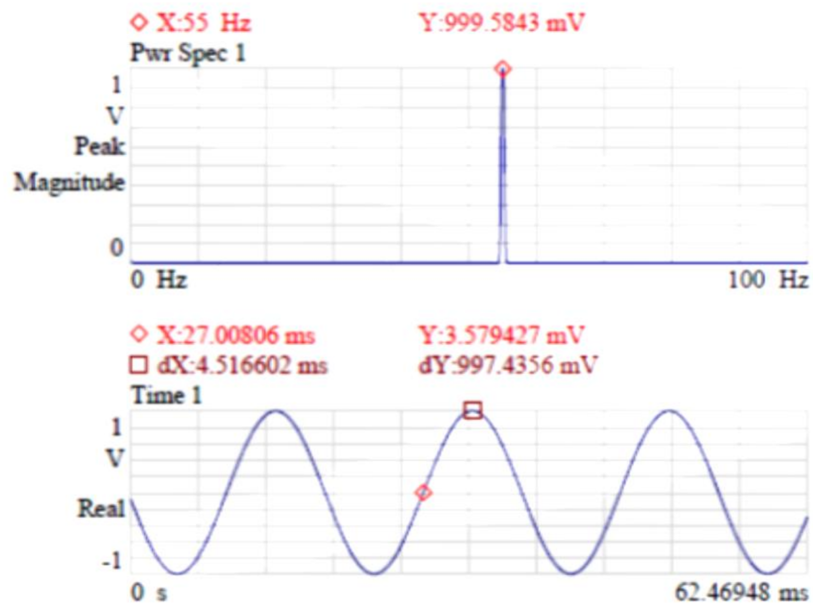
The spectrum value uses the suffix "Pk-Pk" to denote this.



Pk (Peak)

The time wave has not changed. The Peak value is expressed from zero to the peak amplitude.

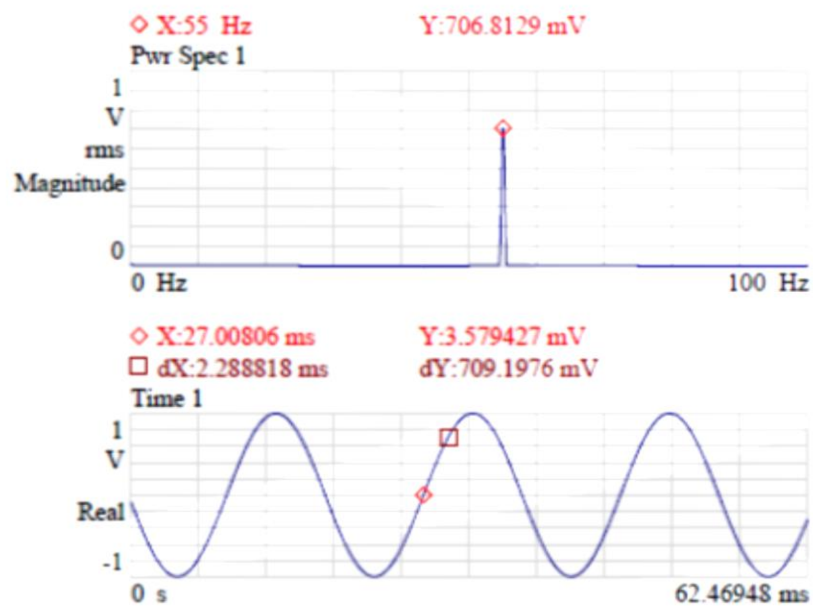
The spectrum value uses the suffix “Peak” to denote this.



RMS (Root Mean Square)

The time wave has not changed. The RMS value is expressed from zero to 70.7% of the peak amplitude.

The spectrum value uses the suffix "RMS" to denote this.

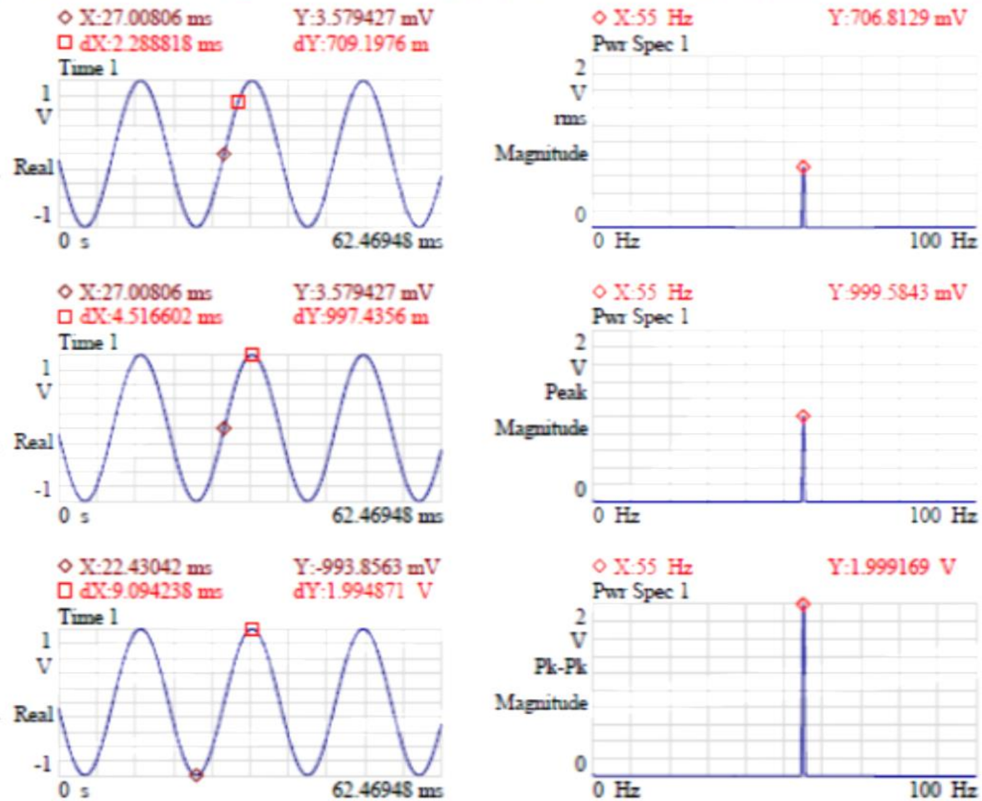


Suffix Comparison

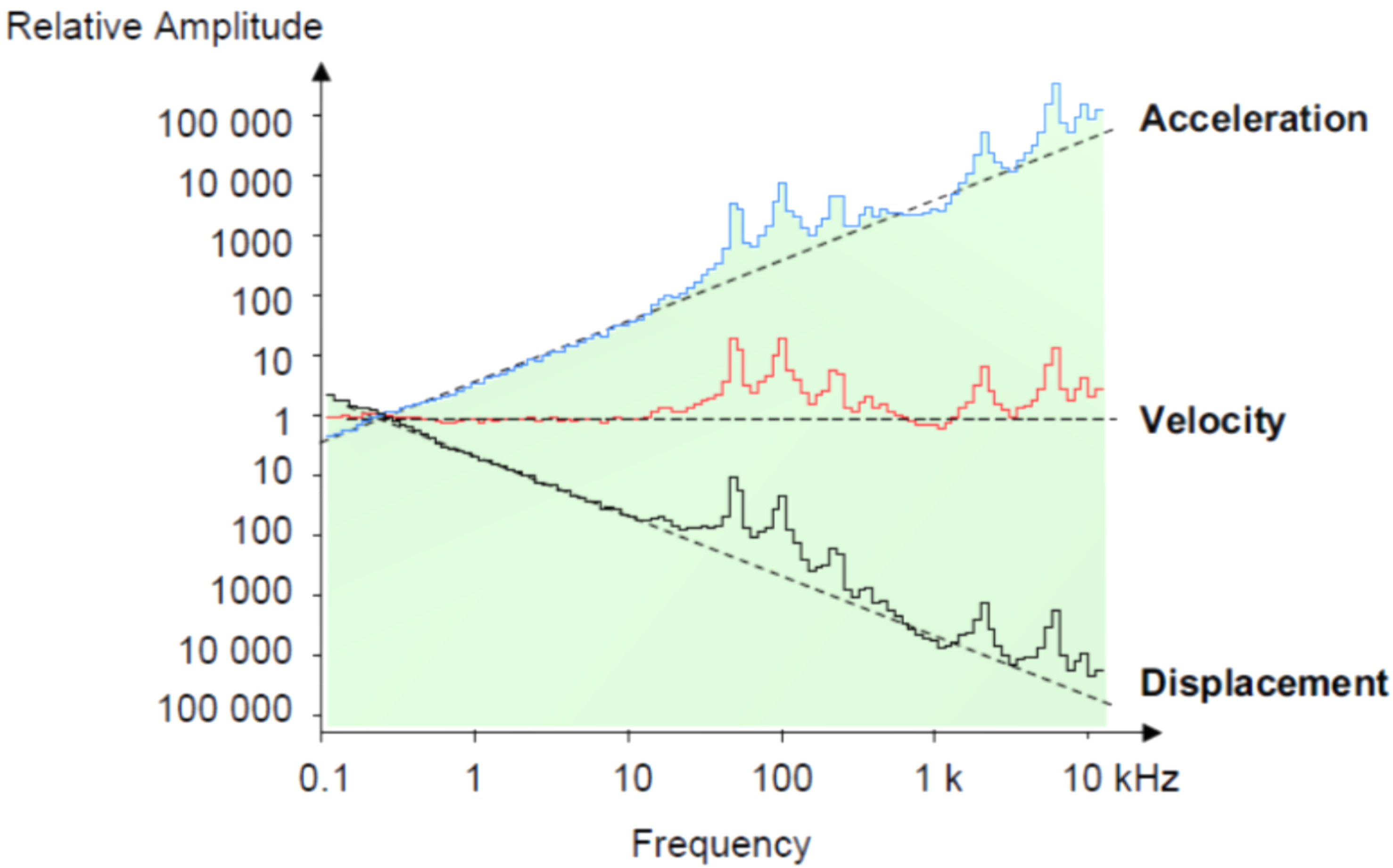
RMS

Peak

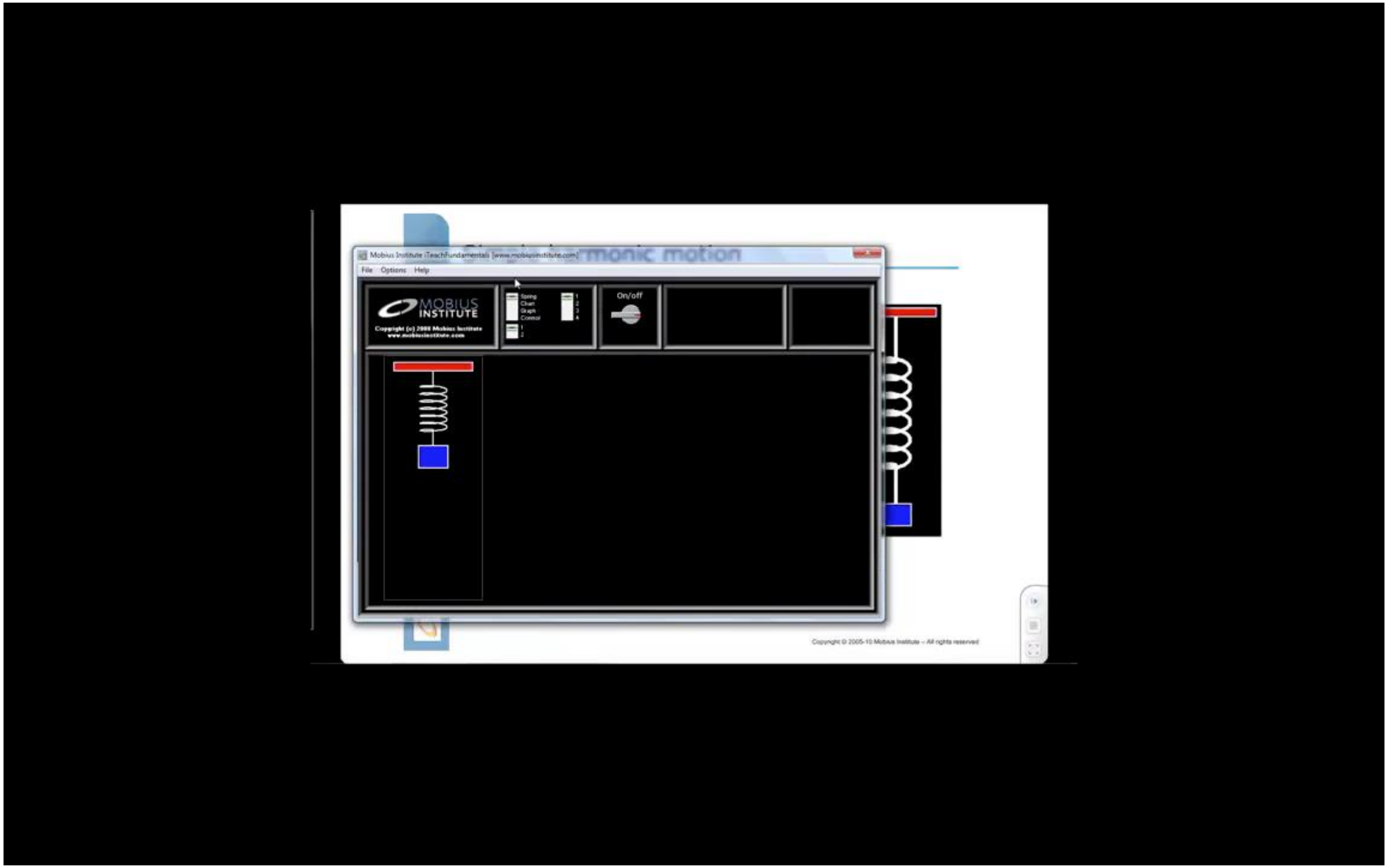
Peak - Peak



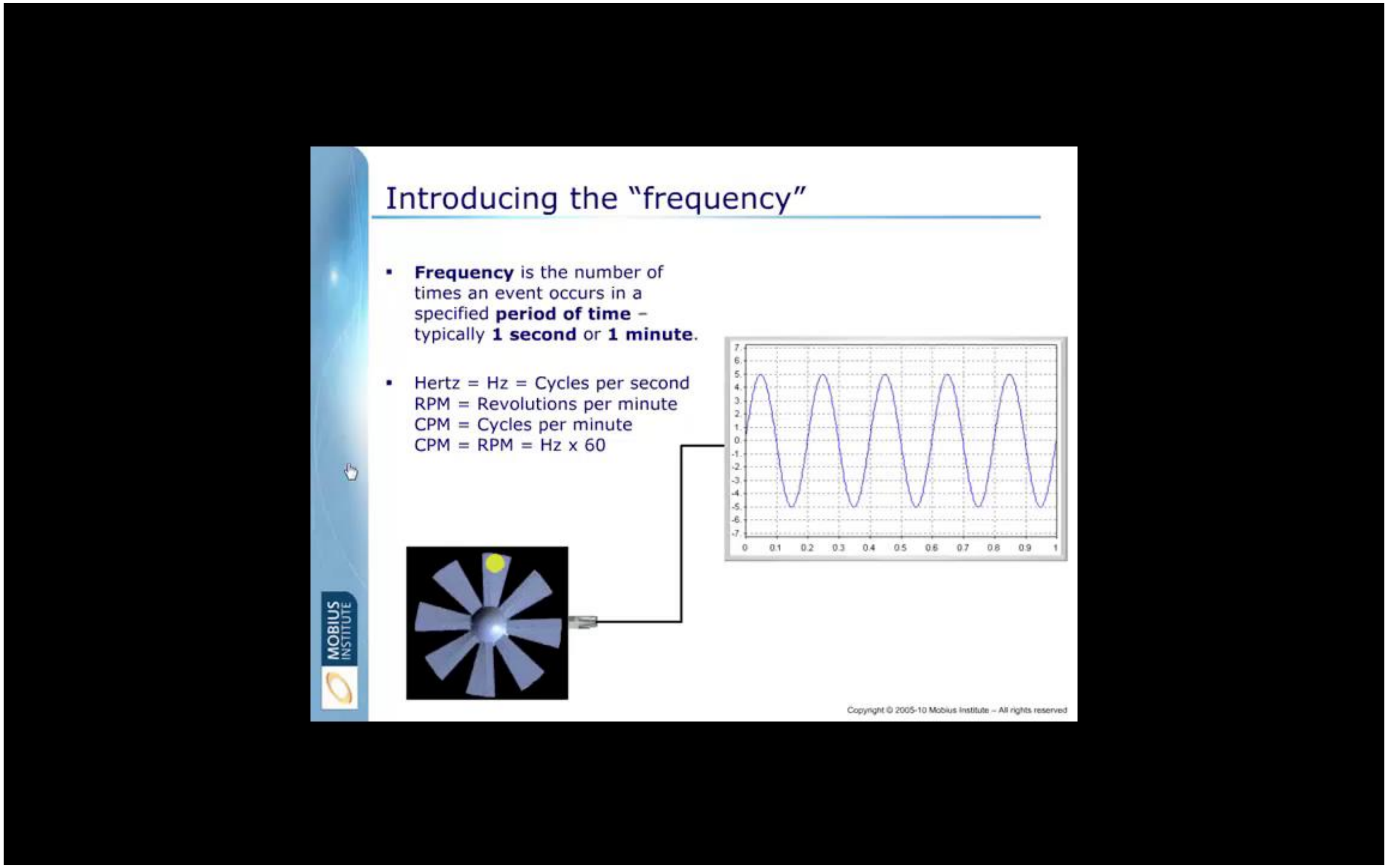
Vibration Parameters



Simple Harmonic Motion



Time period


Introducing the "frequency"
Frequency is the number of times an event occurs in a specified **period of time** – typically **1 second** or **1 minute**.
Hertz = Hz = Cycles per second
RPM = Revolutions per minute
CPM = Cycles per minute
CPM = RPM = Hz x 60
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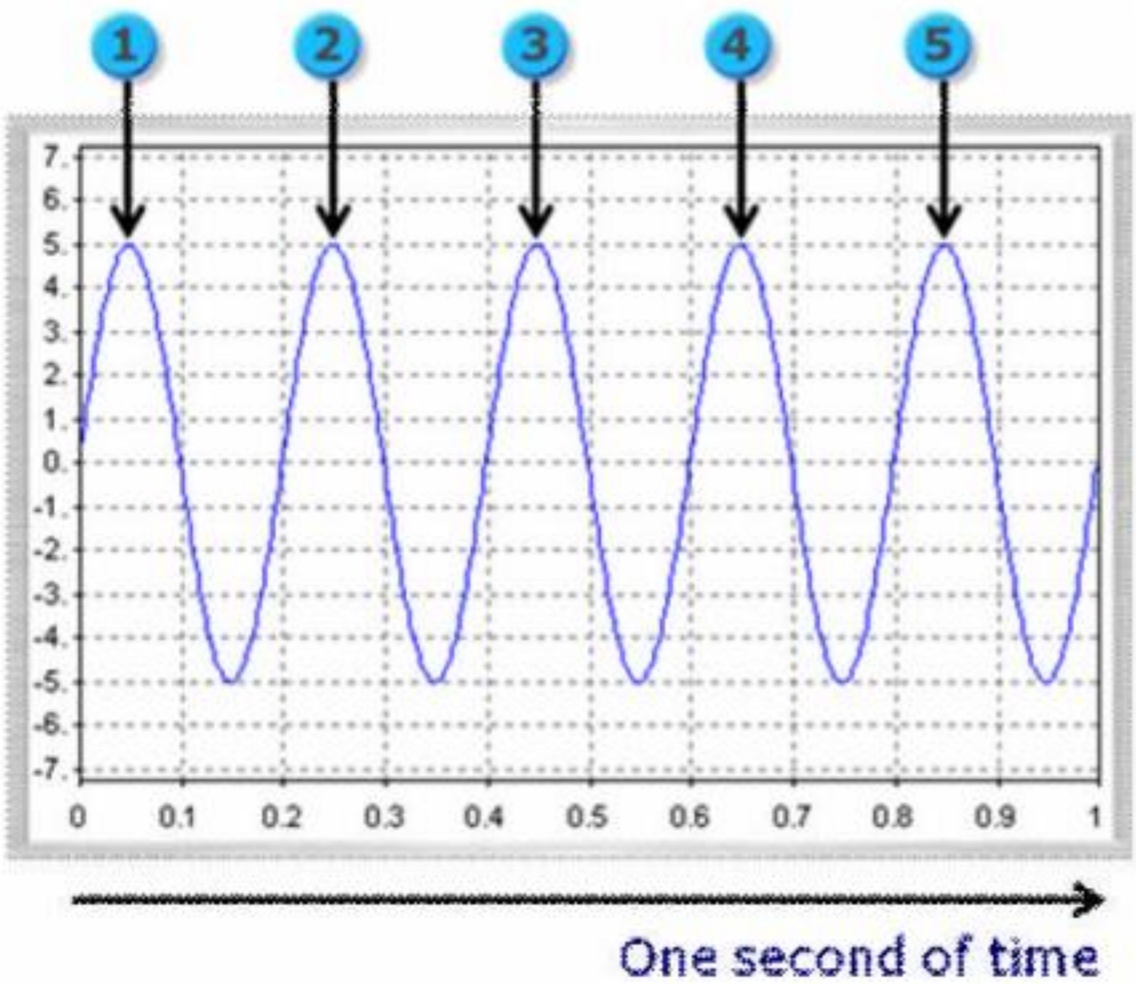
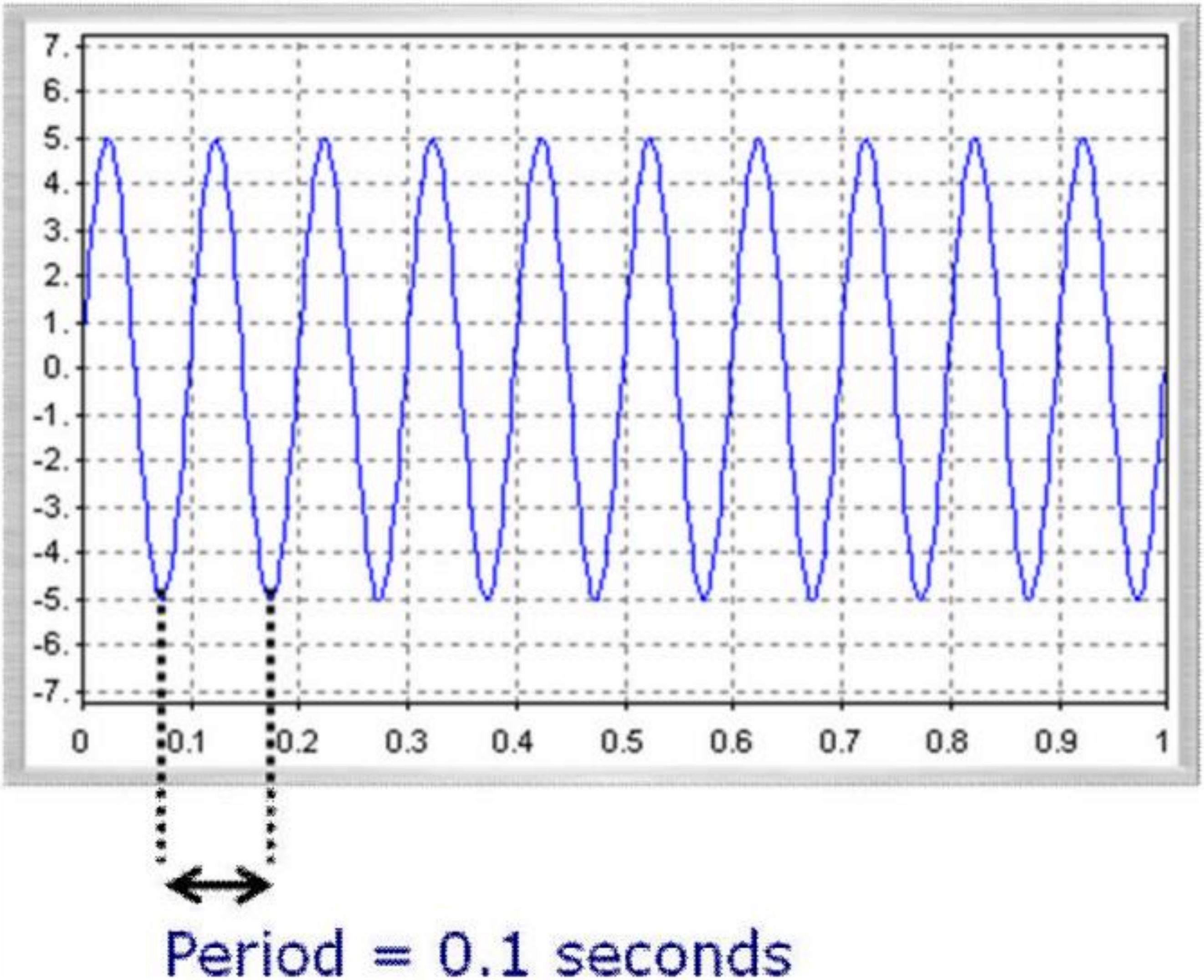
Vibration Measurement Frequency



Vibration Measurement

Period



Vibration Measurement Amplitude

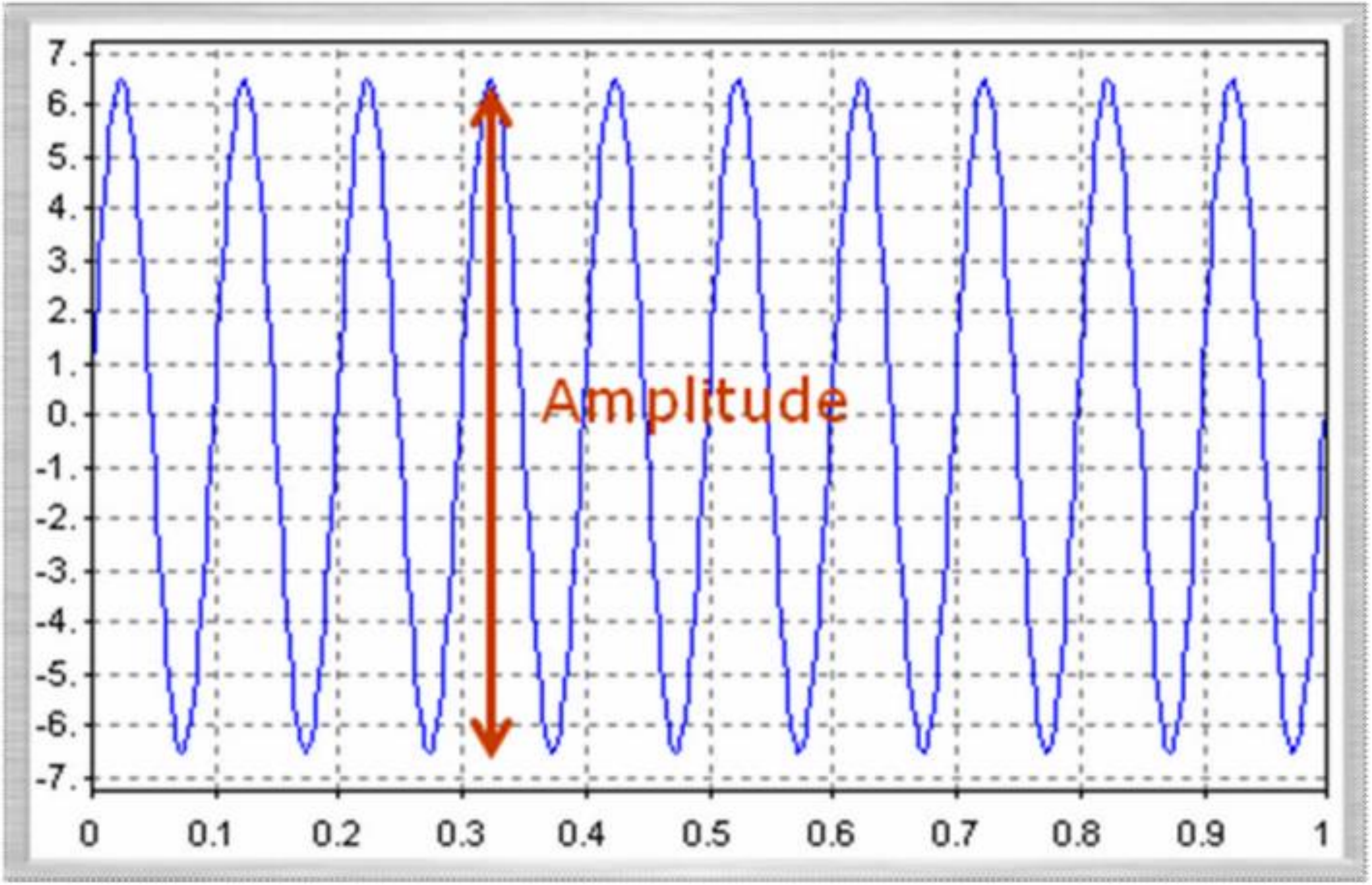


Figure 3-15 As speed increases, the amount of vibration, or amplitude, increases.

Vibration Measurement

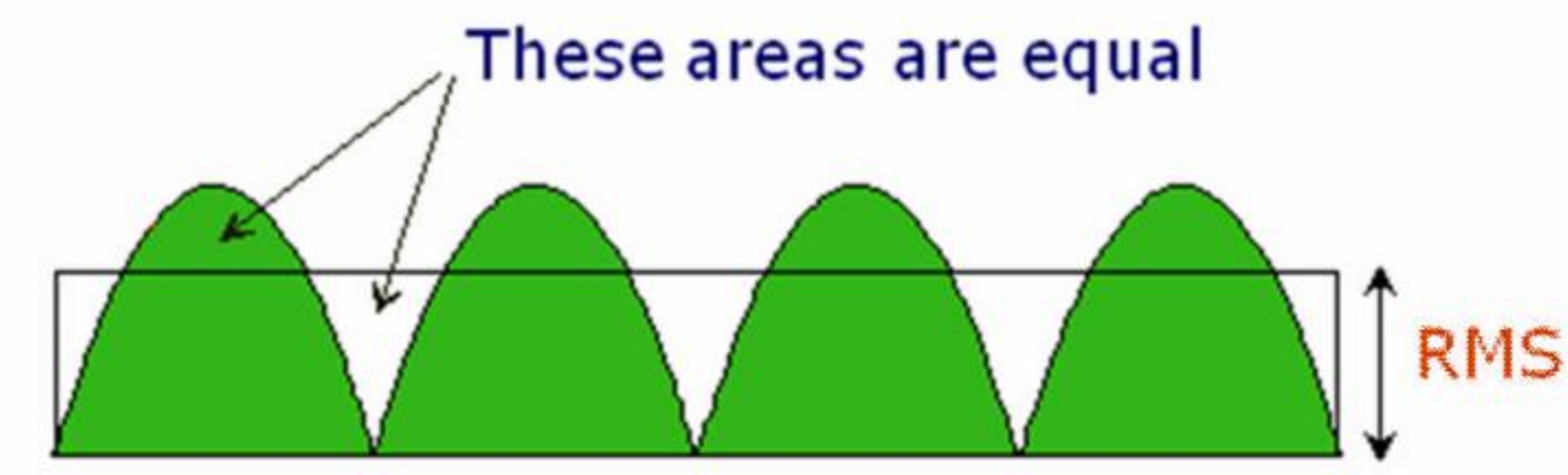
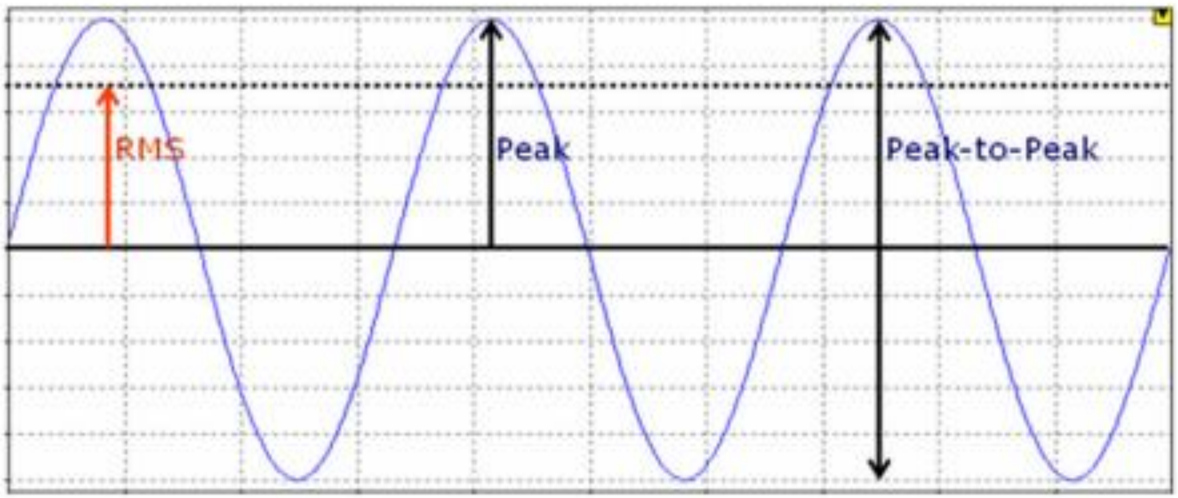
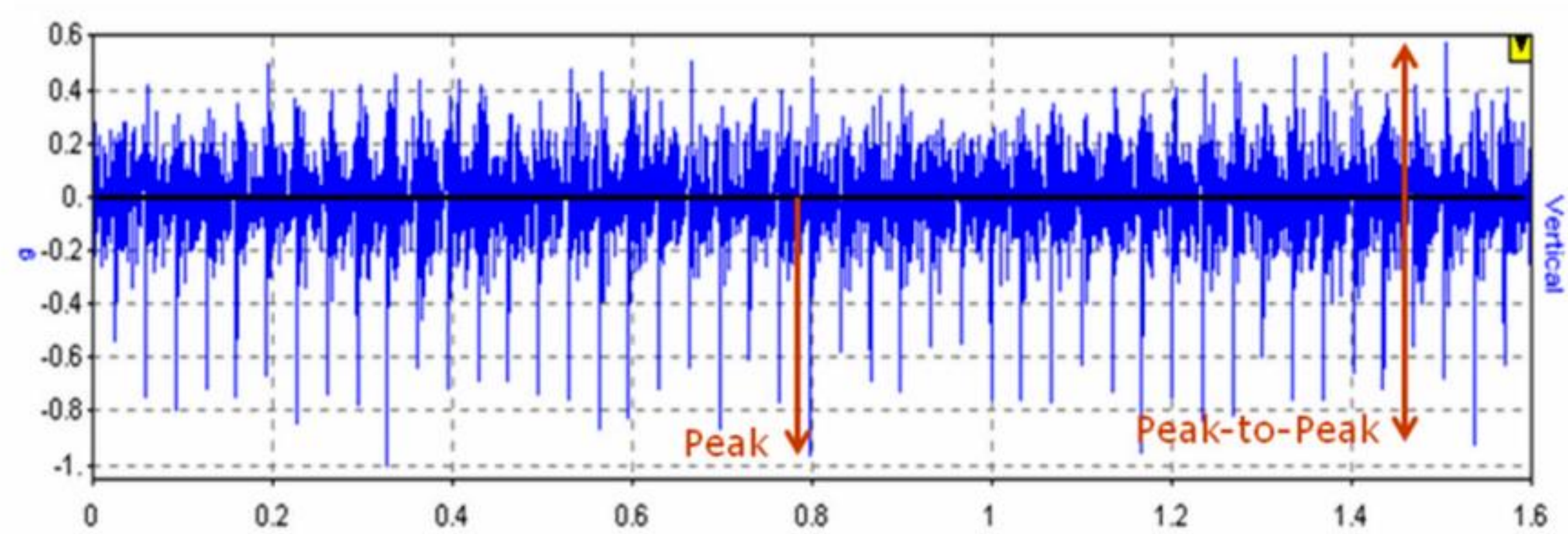


Figure 3-41 The RMS is calculated after rectifying (making the negative parts positive) the waveform

Vibration Measurement



Vibration Measurement



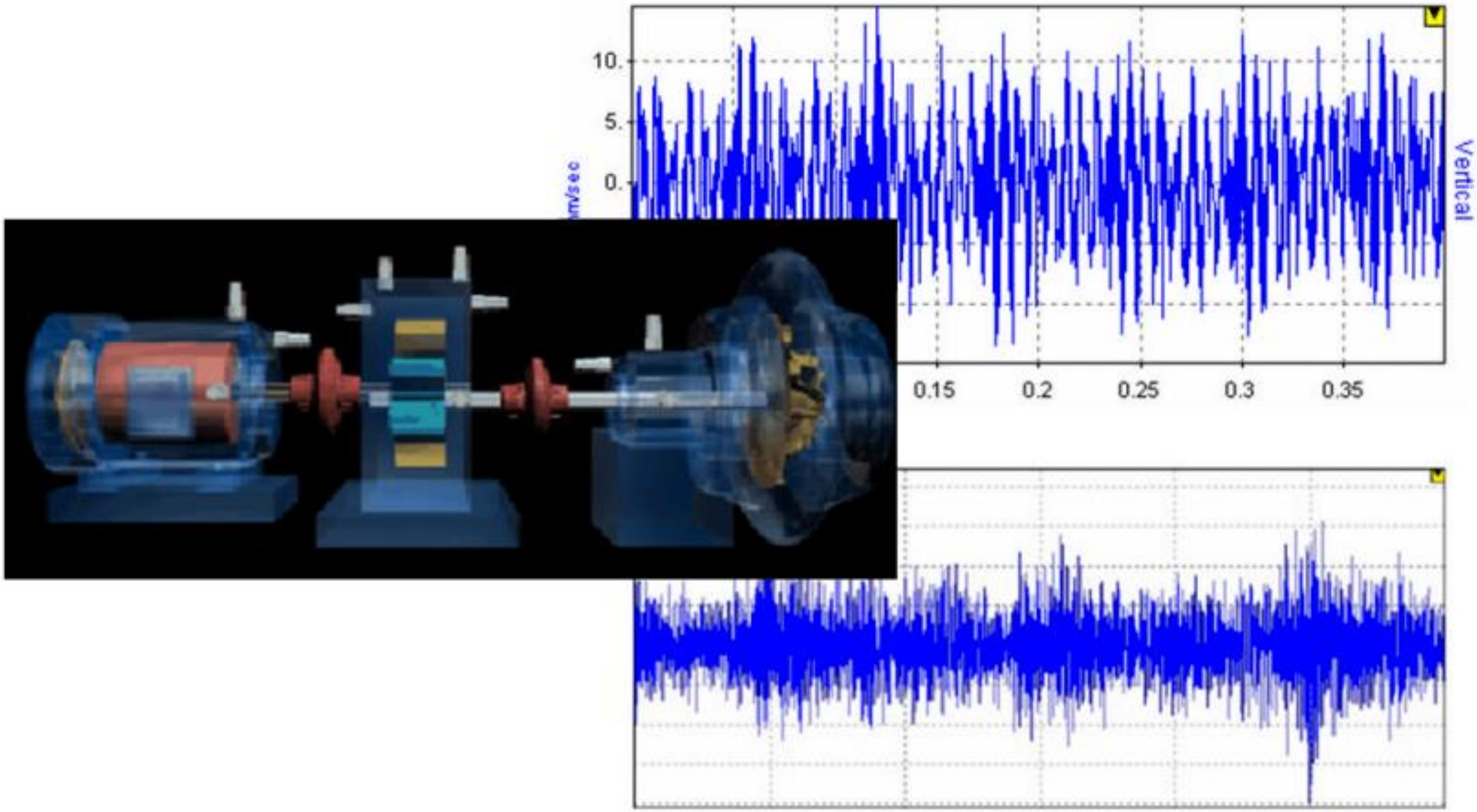
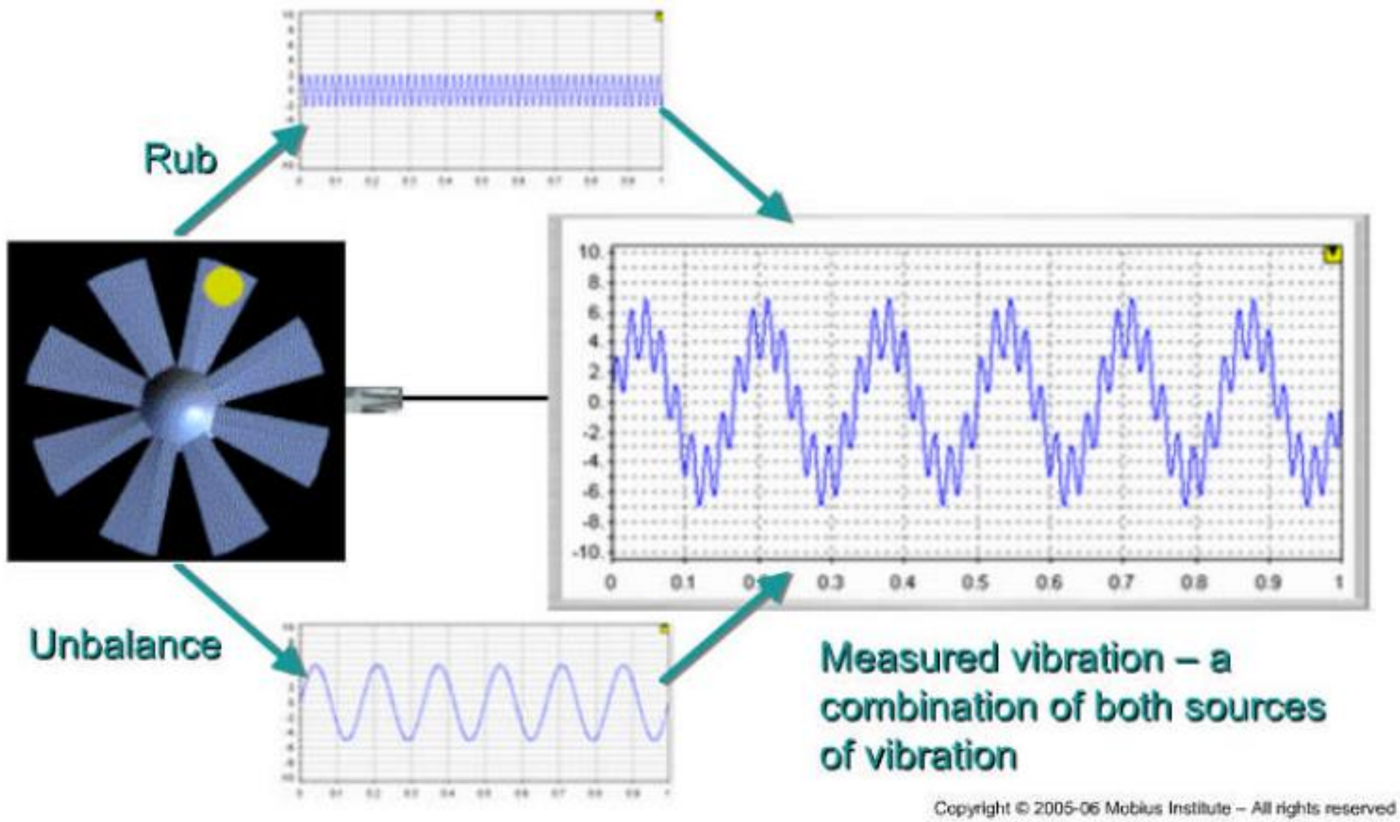


Figure 3-20 The goal is look inside the machine to see what is happening. Vibration can do that. The waveform can be too complex to sort out the sources.

Vibration Measurement



Spectrum

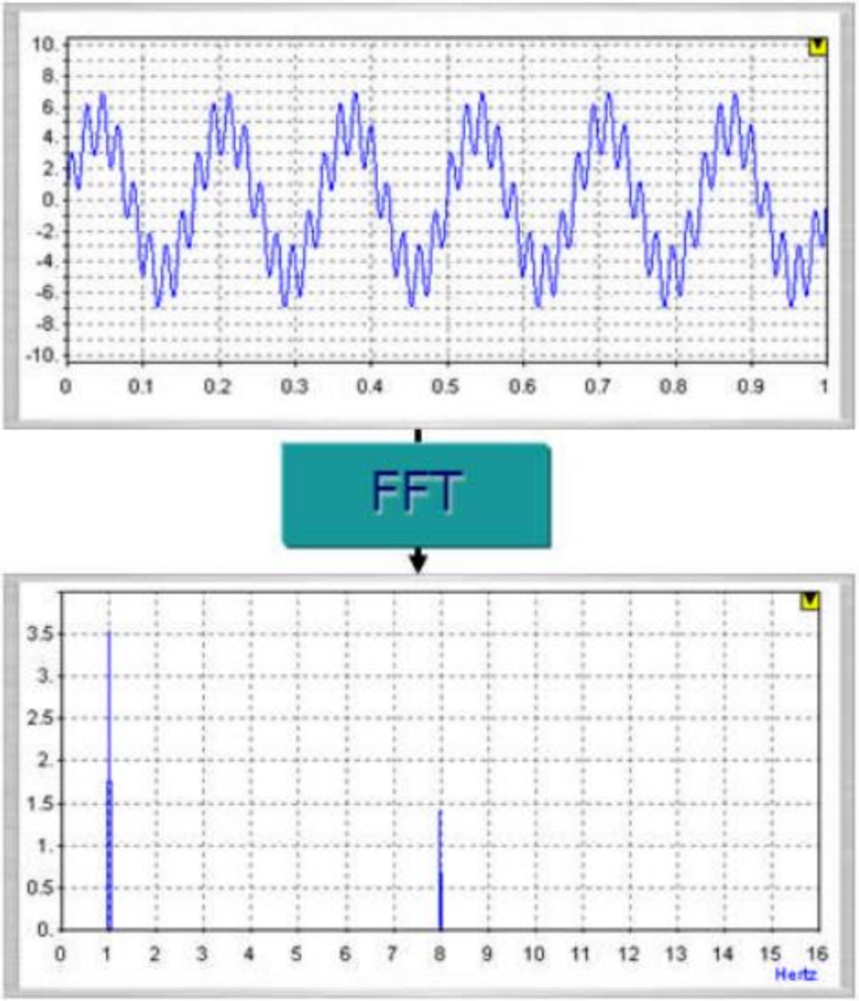


Figure 3-21 The FFT process separates the individual waveforms and displays them according to frequency.

Spectrum

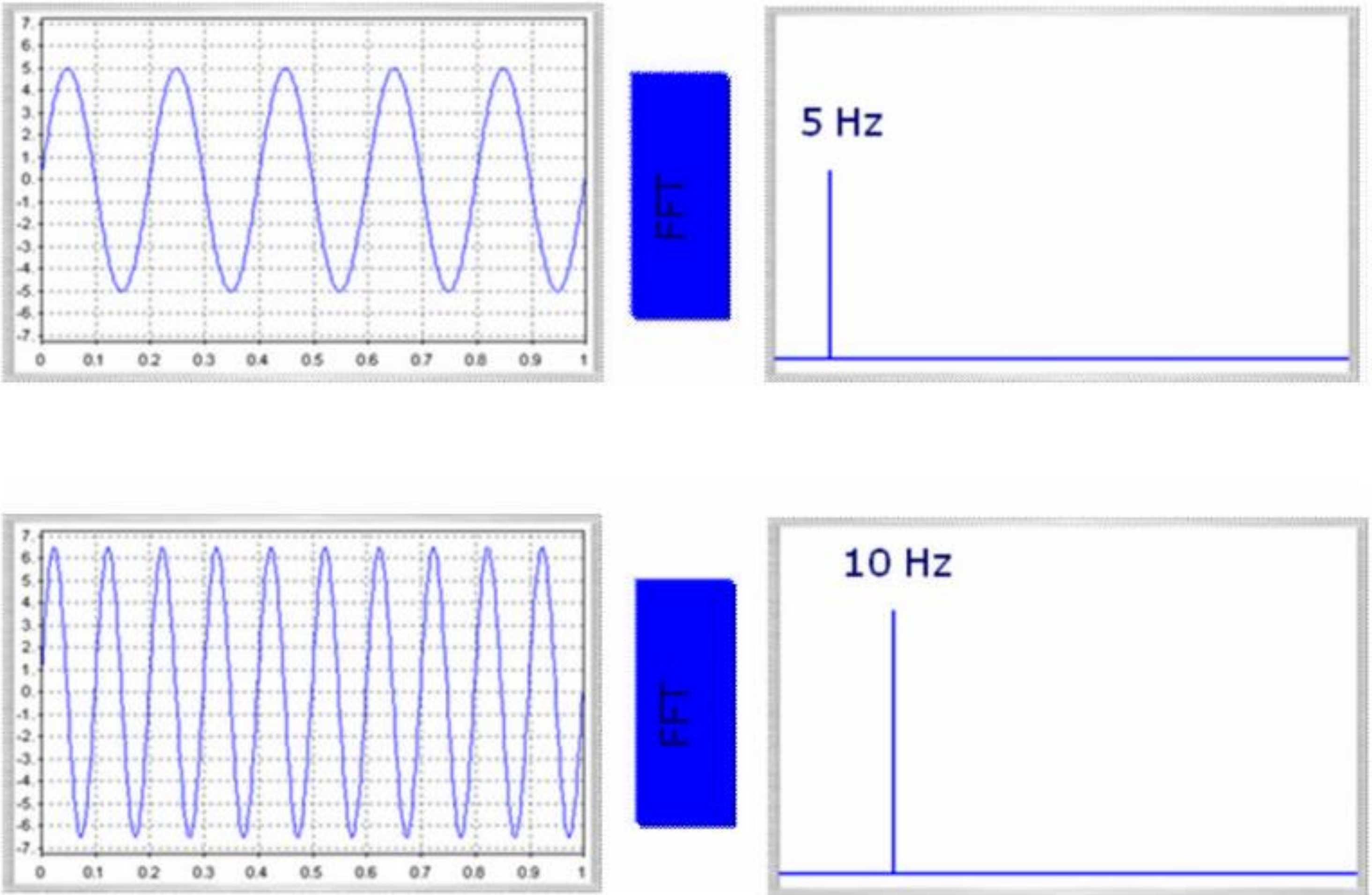


Figure 3-22 The top waveform of a 5 Hz cycle produces a spectrum with the 5 Hz peak. The bottom waveform is a result of doubling the speed to 10Hz. It produces a spectrum with a peak at 10 Hz. Notice the height of the peaks reflects the amplitude of the waveform.

Spectrum

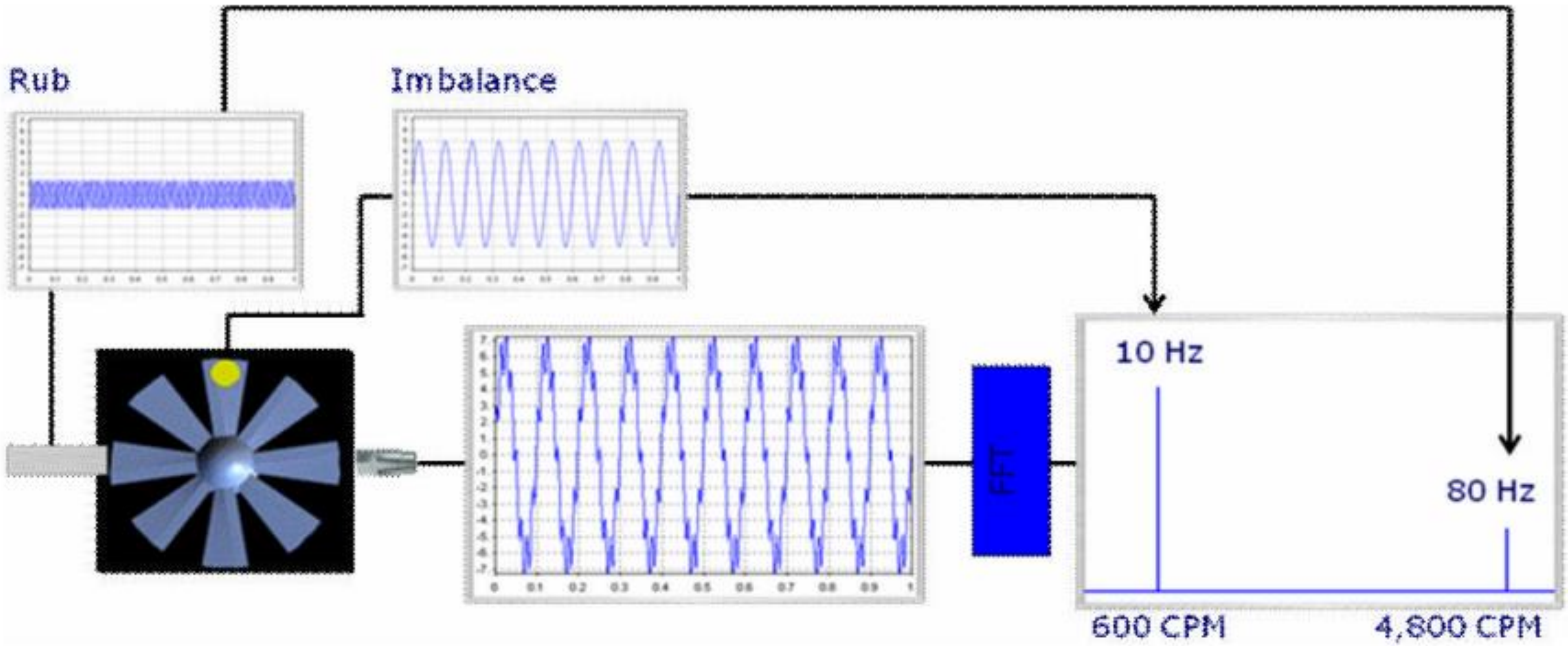
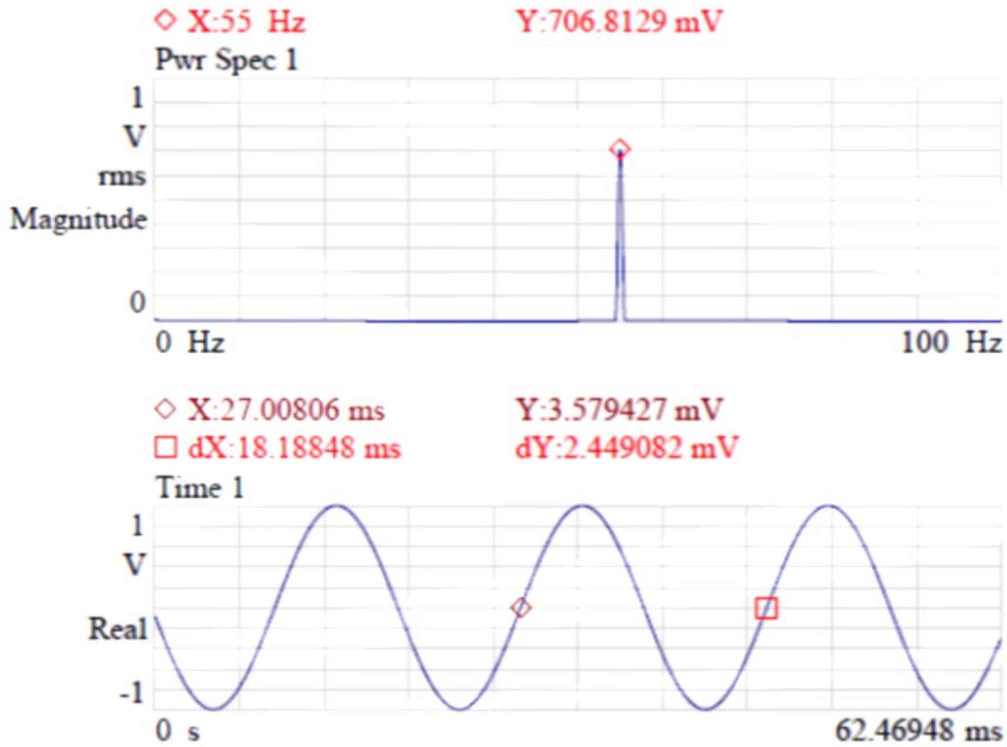


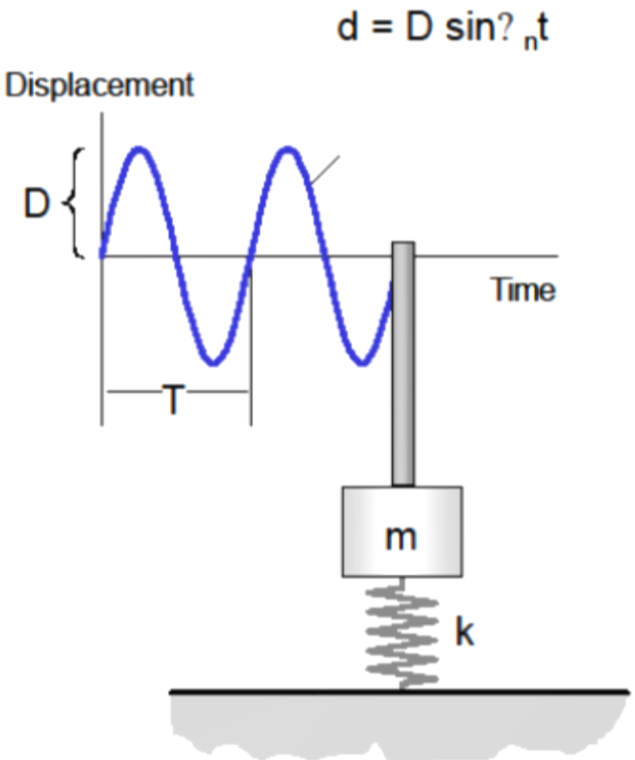
Figure 3-23 The FFT process separates the complex waveform into the individual waveforms and displays them in the spectrum.

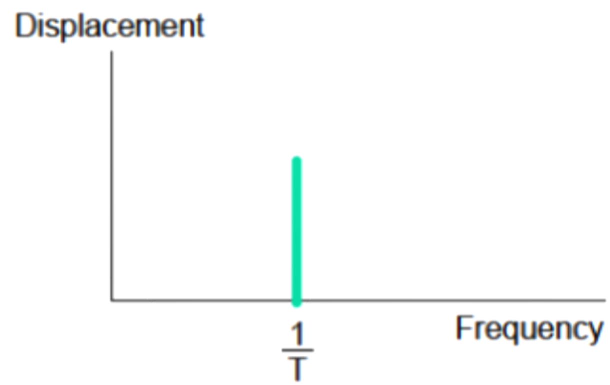
Spectrum

Single Frequency



FFT transformation





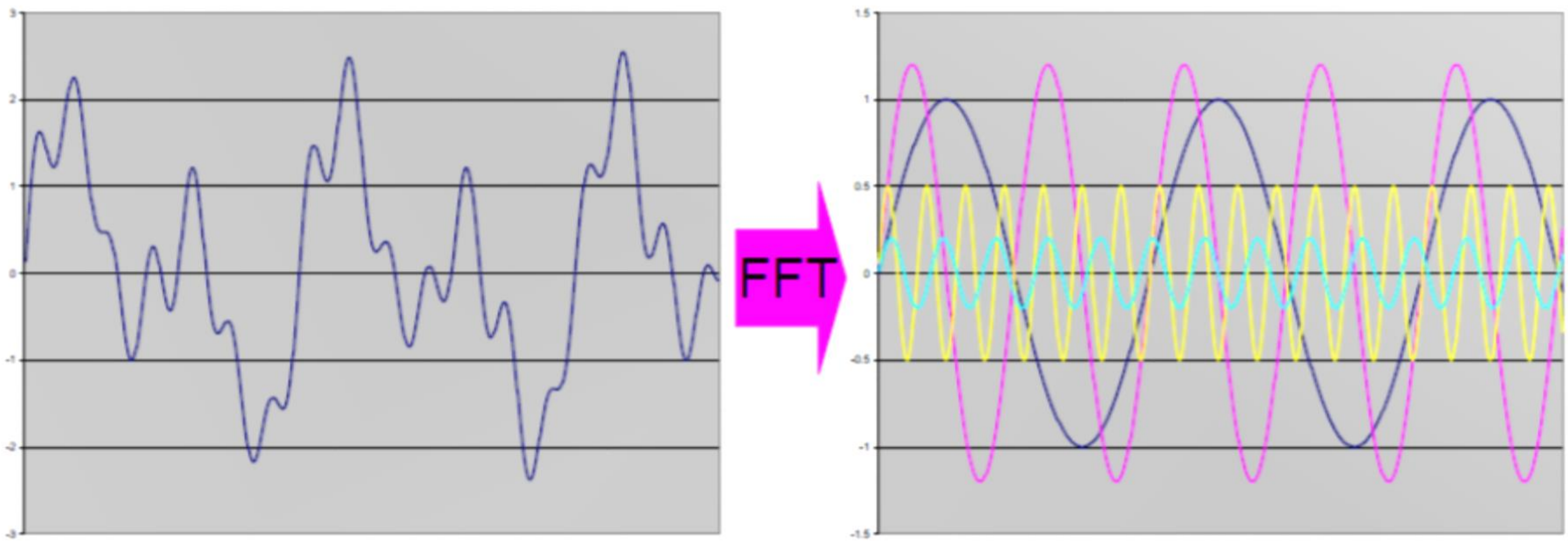
Period, T_n in [sec]

Frequency, $f_n = \frac{1}{T_n}$ in [Hz = 1/sec]

? $_n$= 2 ? f_n = $\sqrt{\frac{k}{m}}$

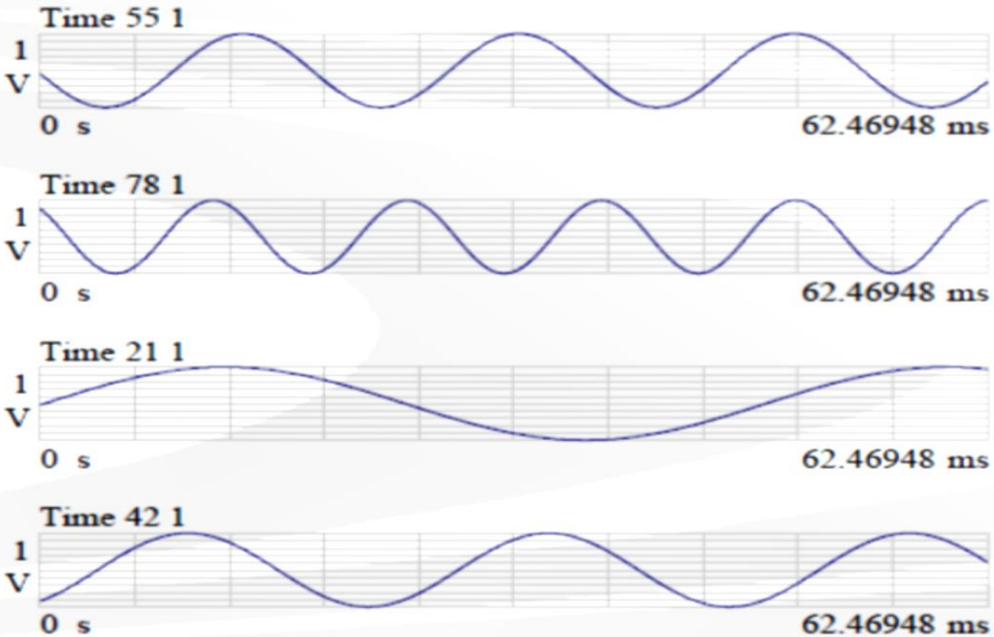
Signal Processing – break down complex waveform in to waveform components

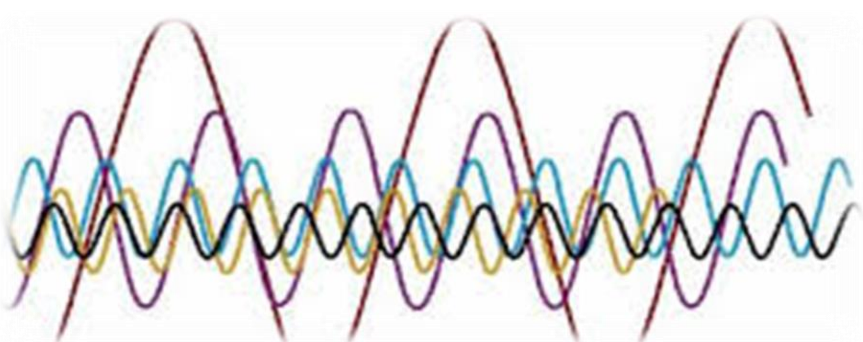
The Fast Fourier Transform (FFT) takes the complex waveform and breaks it down into the component sine waves



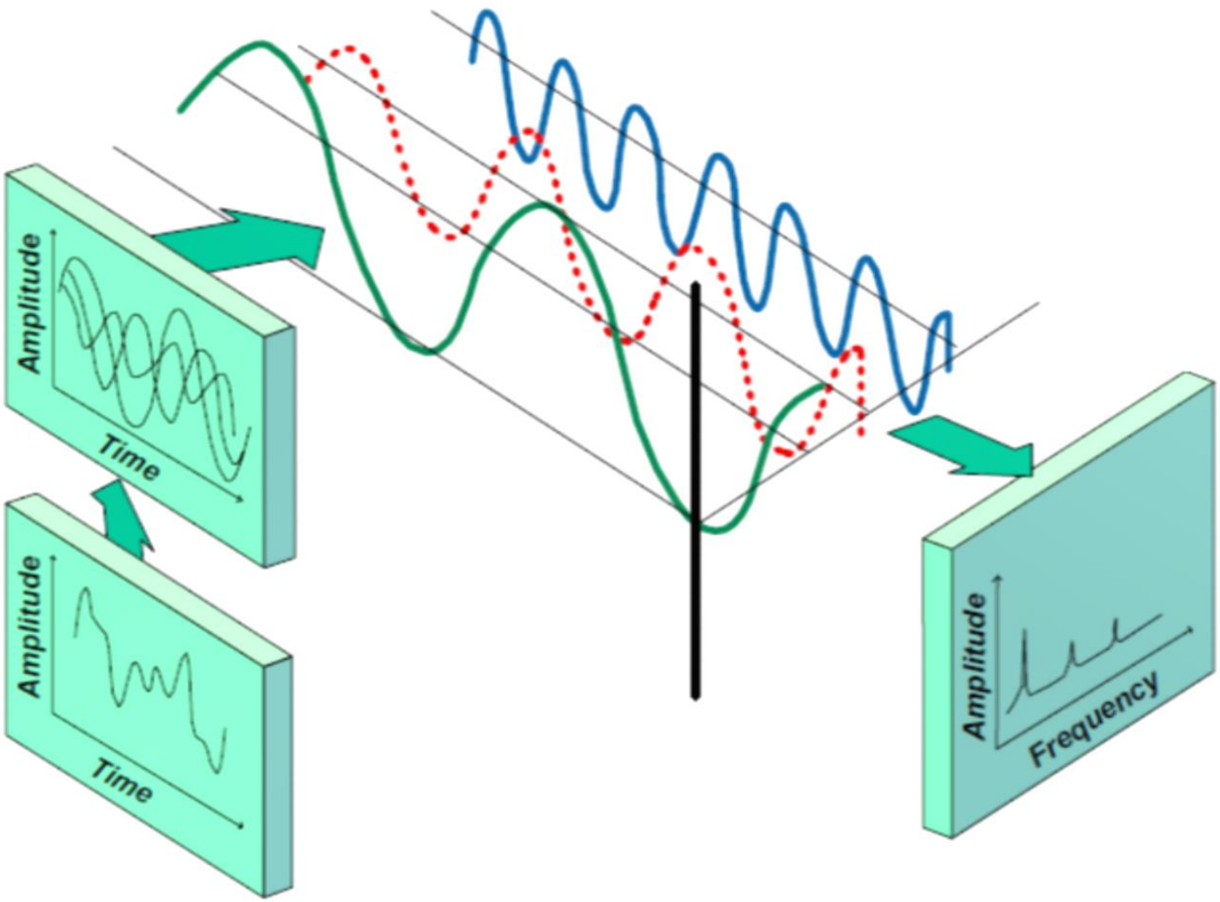
The amplitudes for each sine wave is then plotted at the frequency of the sine wave, creating the Spectrum

Multiple Time

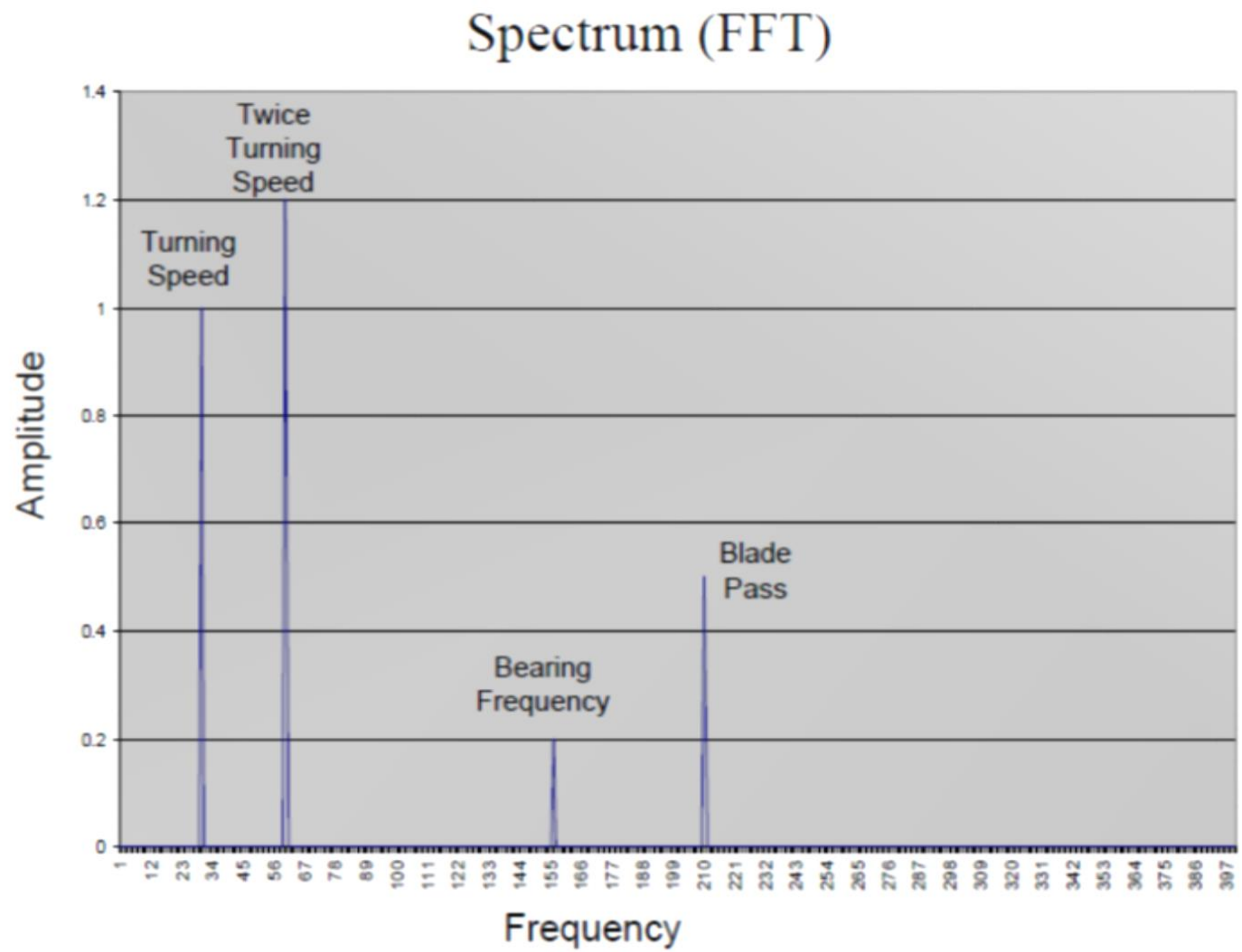




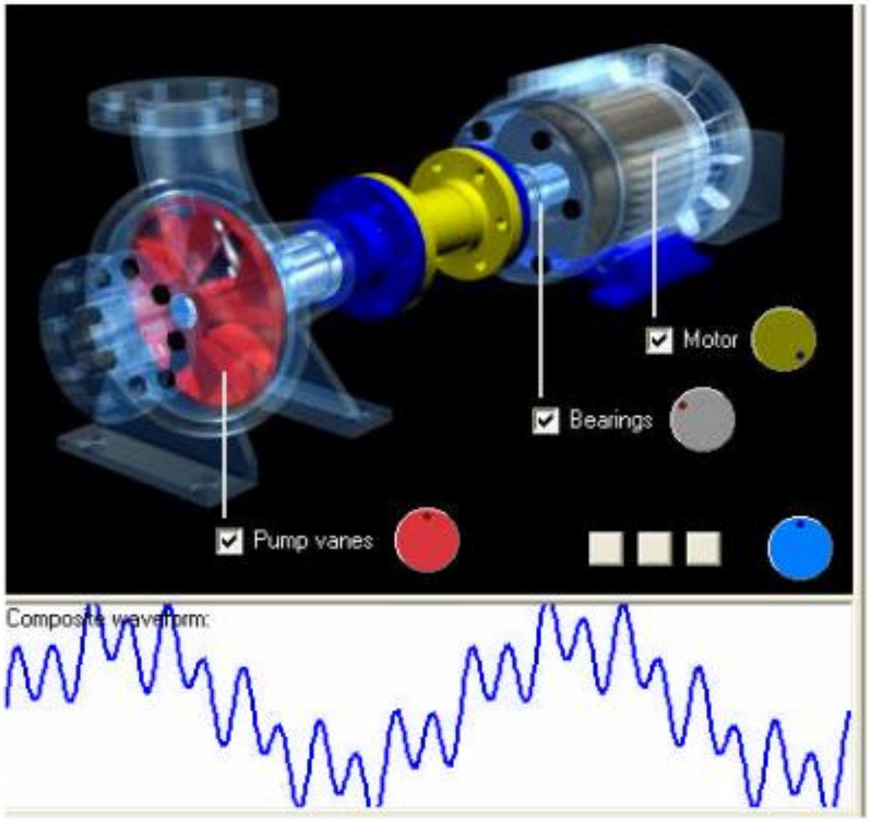
FFT Signal Processing



Signal Processing – The FFT or Spectrum



Spectrum



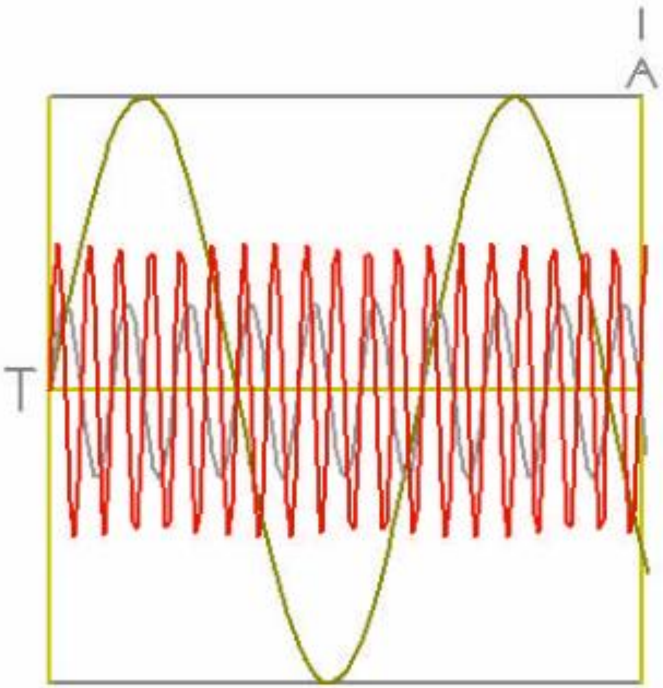


Figure 3-24 Three sources of vibration are combined in the composite waveform. They are individually overlaid in the box to the right of the machine.

Spectrum

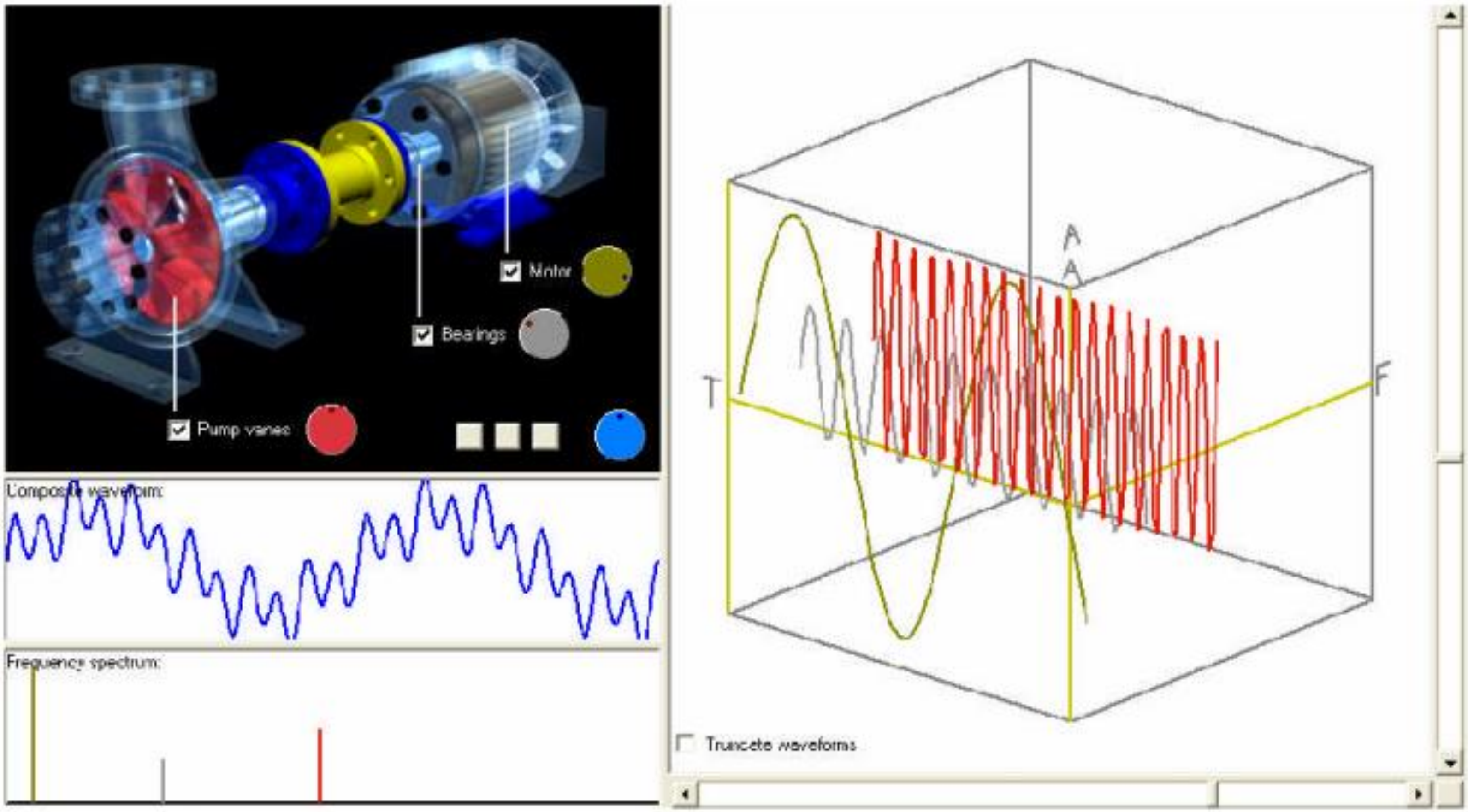
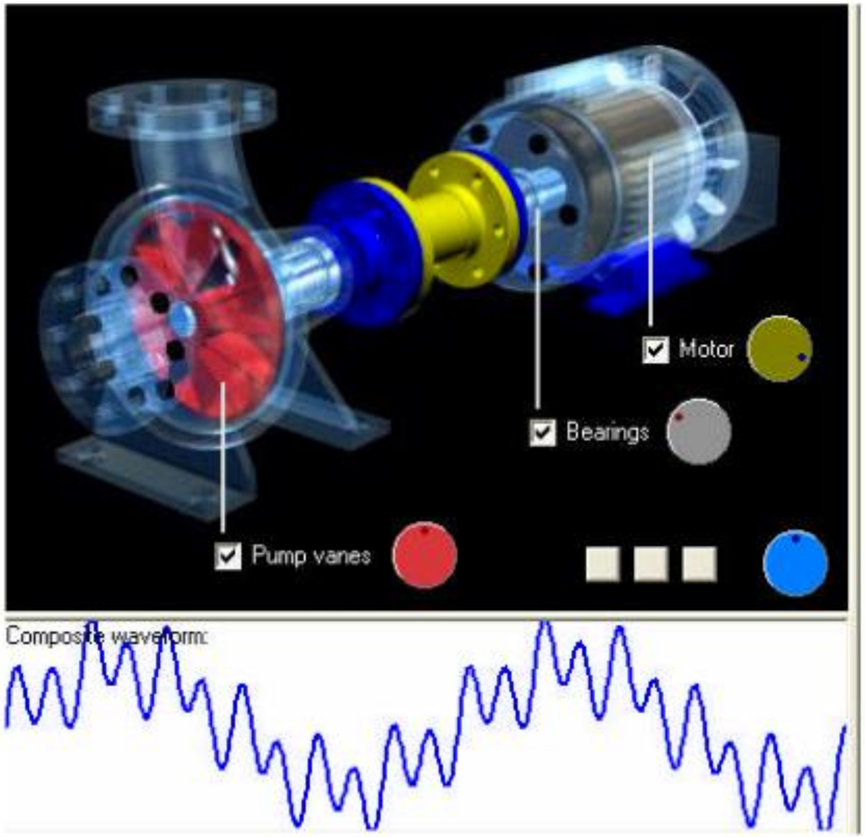


Figure 3-25 The individual waveforms are shown in a 3 dimensional box that is partially rotated.

Spectrum



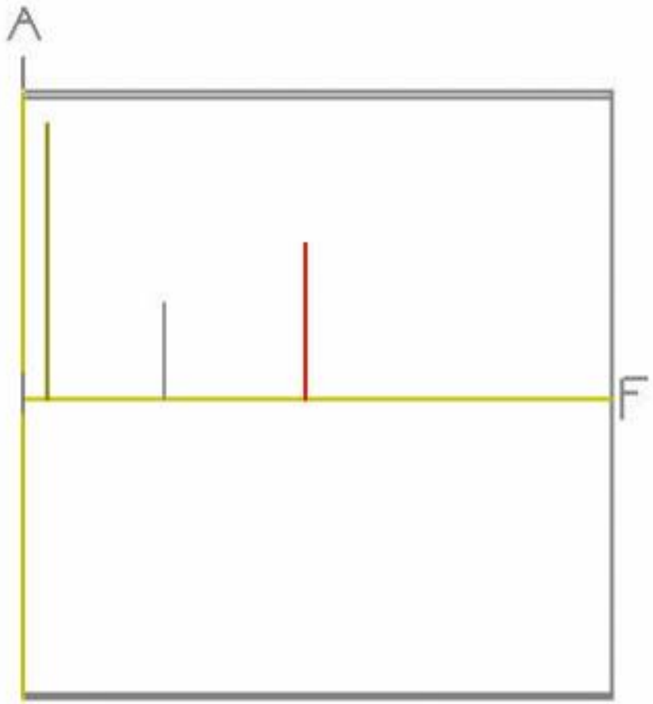
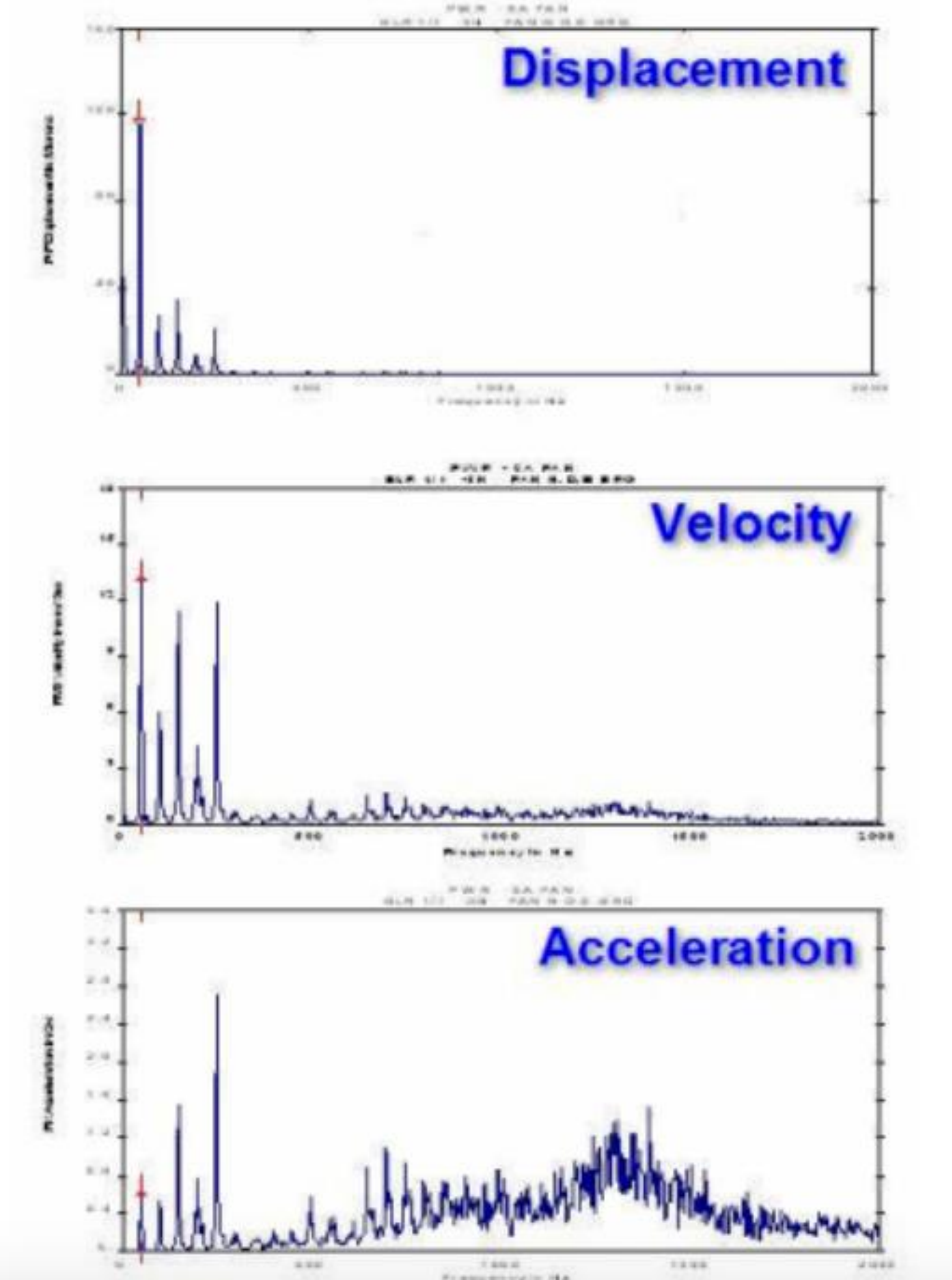
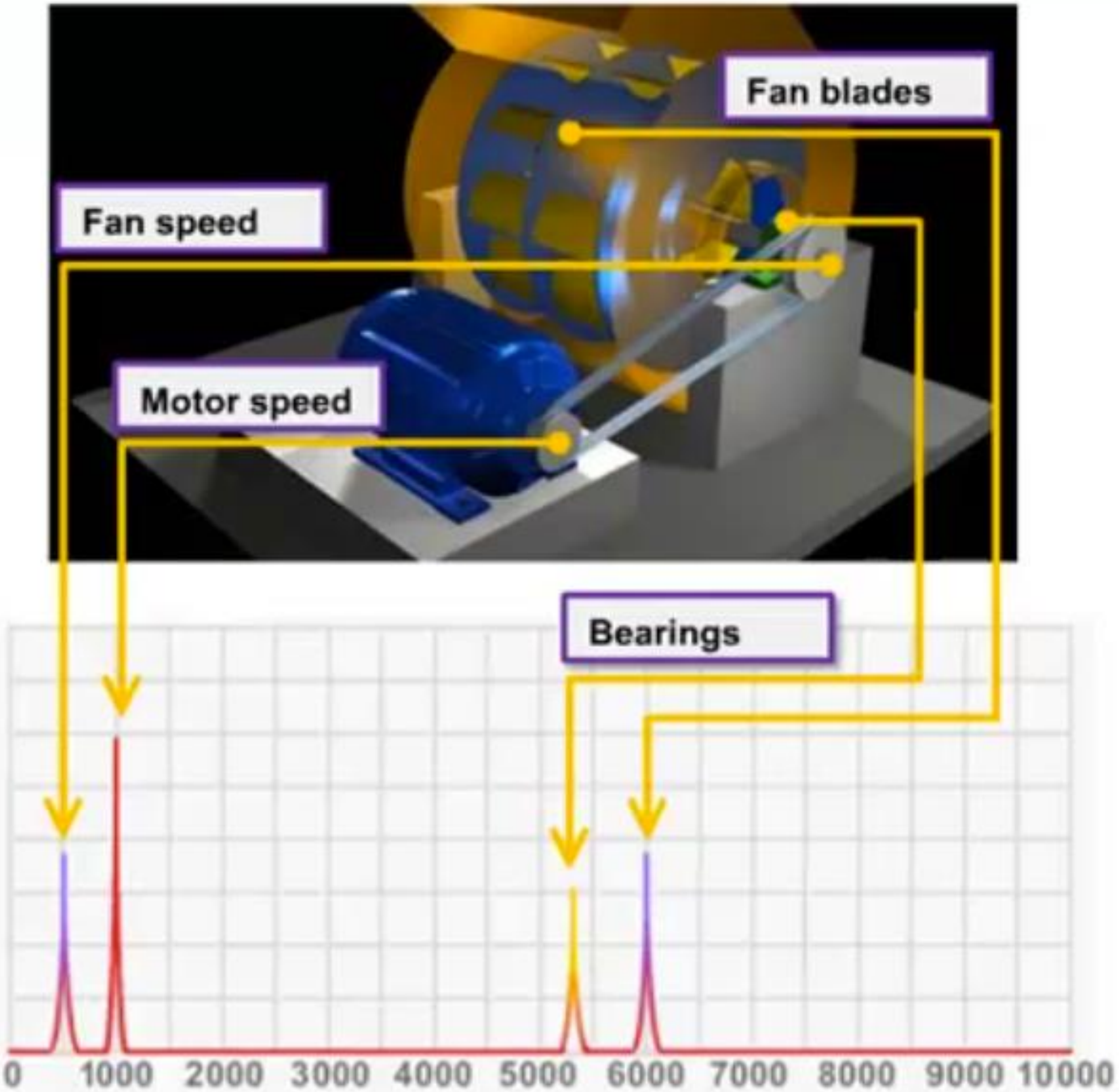


Figure 3-26 The 3 dimensional box is shown rotated 90 degrees revealing the end-view of the waveforms. They have been truncated so that nothing is shown below the zero line. The X axis is Frequency.

Spectrum

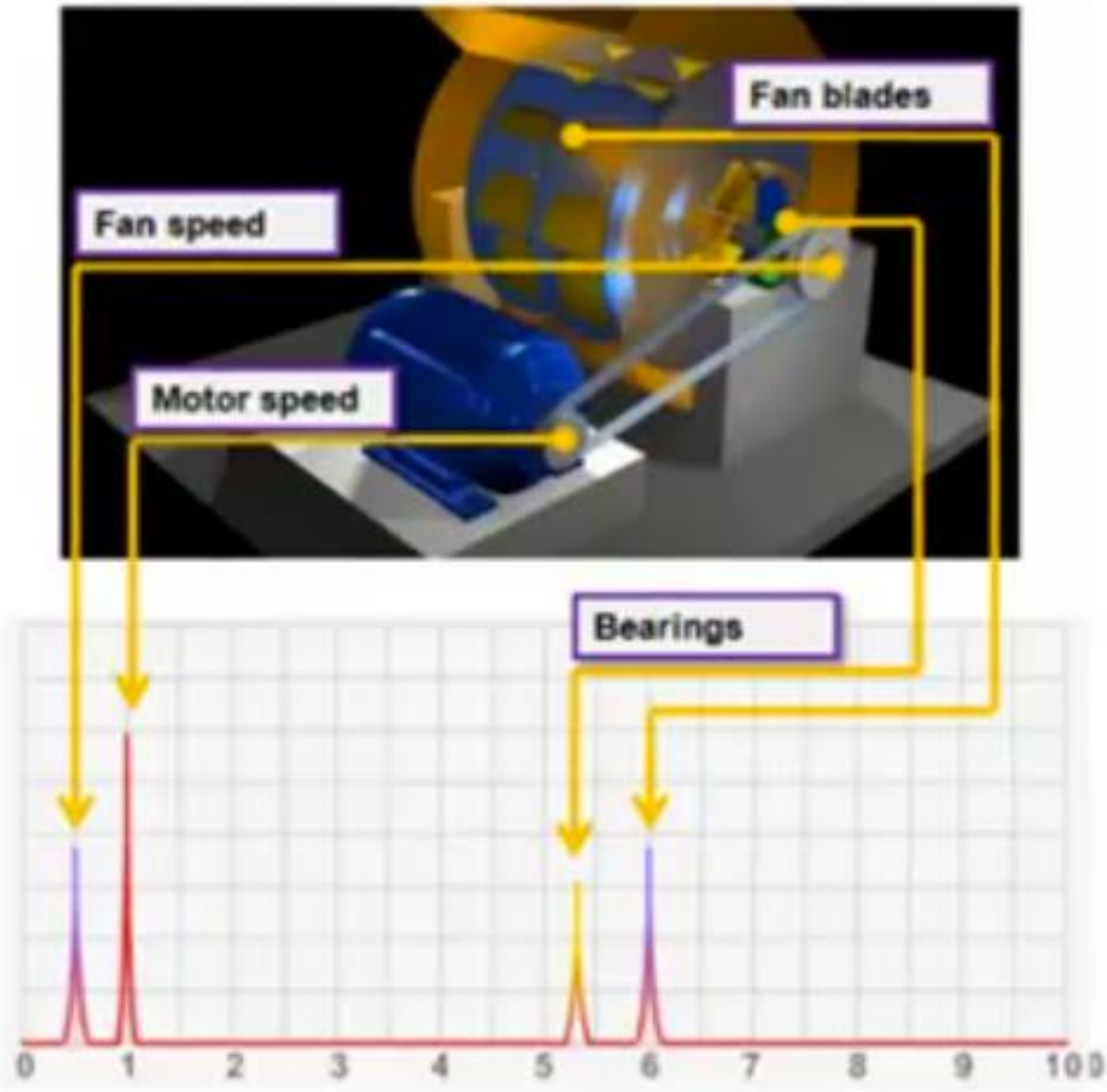


Spectrui



Fan blades
Fan speed
Motor speed
Bearings
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

Spectrum Orders



Thank you