

# Mechanical Design Concepts for Non-Mechanical Engineers




By Steve Mackay

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## Overall Presentation

This workshop is designed for personnel with a need to understand the use, care, installation, or the economics associated with mechanical machinery.

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## Objectives

- The importance of common engineering material properties in relation to component life and failure
- How to monitor, control and analyse vibrations

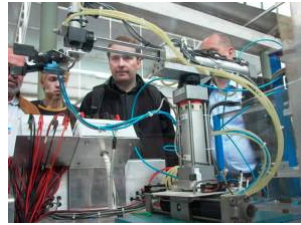


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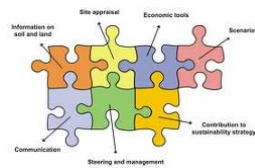


# Topics




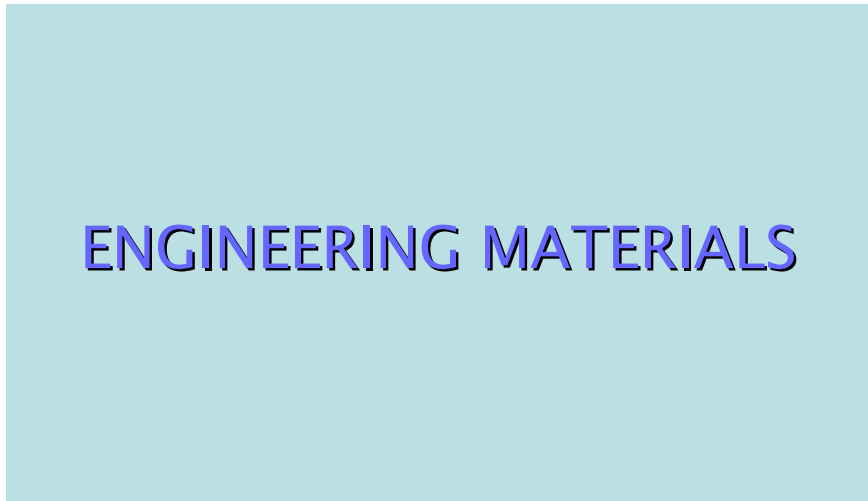
- Introduction
- Mechanical Materials
- Vibration
- Conclusion






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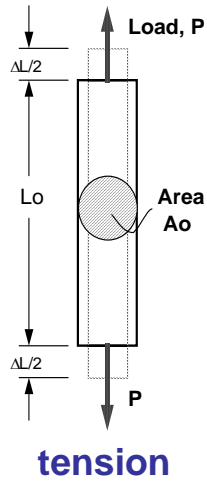


# ENGINEERING MATERIALS

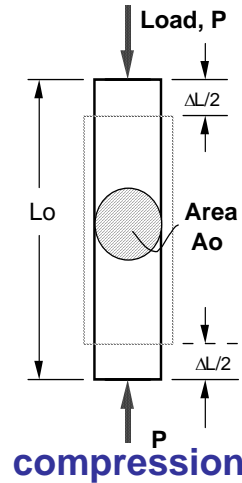
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## Tension and Compression



**Axial force:**  
A load directed along the axis of the object resulting in either *tension* or *compression*



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## Stress and Strain

- Stress may be defined as *load/area*.
- Strain is the deformation of the component/original length.
- A stress may be normal, shear, or torsion – leading to corresponding deformations.
- Stress cannot be measured directly, but deformation can be.

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## Normal Stress

Stress that acts in a direction perpendicular to the cross-sectional area.

Normal stress is the force per unit area and is given by:

$$\sigma = \frac{P}{A_0}$$

Where

$\sigma$  is the stress in  $N/m^2$

$P$  is the instantaneous force applied perpendicular to the specimen cross-section in  $N$

$A_0$  is the original cross-section prior to deformation in  $m^2$ .

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## Normal Stress

- An object in tension has resulting ***tensile stresses***, and an object in compression has resulting ***compressive stresses***.

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## Elastic Deformation

- Elastic deformation is a nonpermanent deformation that is totally recovered upon release of the applied stress.
- Elastic region is linear for most metals.
- But for some materials like grey cast iron, concrete and many polymers, the elastic region is non-linear.

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## Elastic Deformation

- If the elastic region is linear (or nearly linear) on application of tensile stresses, Hooke's Law is applied:

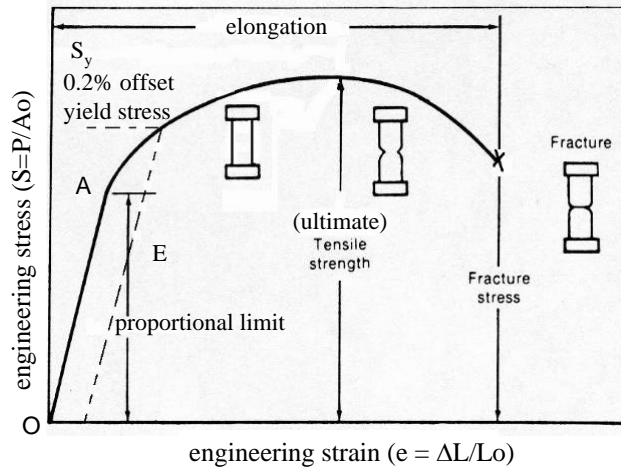
$$\sigma = E\varepsilon$$

- Where **E** is the modulus of elasticity or Young's Modulus (GPa).
- For most metals this typically ranges between **45 GPa** and **407 GPa**.

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## Stress–Strain Diagram



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## Stress–Strain Diagram

- **Modulus of elasticity:**
  - *Slope of the linear region of the stress–strain diagram.*
- **Proportional limit:**
  - *Stress at which the linear relationship between stress and strain fails to exist.*

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## Stress–Strain Diagram

- **Yield stress:**
  - stress at which yielding of the material takes place, i.e. considerable elongation of the test specimen takes place with no noticeable increase in tensile force.
- **Strain hardening:**
  - change in the crystalline structure of the material that occurs during yielding, resulting in increased resistance of the material to further deformation.

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## Common Eng. Material Properties

- **Stiffness:**
  - Indication of how much a component deflects under a given load.
  - Resistance of material to elastic deformation under load is measured by **Young's Modulus (MPa)**.

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## Common Engg. Material Properties

- Stiffness (contd.):
- A *stiff* material (*diamond*) has high Young's modulus and changes shape only slightly under elastic load.
- A *flexible* material (*rubber*) has low Young's modulus and changes its shape considerably.

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## Common Engg. Material Properties

- Ductility:
- *Ability of a metal to plastically deform without breaking or fracturing.*
- *This property allows a metal to be drawn into wires or filaments.*
- *Elongation and reduction of area are common indices of ductility.*

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## Common Engg. Material Properties

- **Toughness:**
- *Resistance to fracture of a material, when stressed.*
- *Can also be defined as the ability of a material to absorb energy.*
- *Key to toughness is a good combination of strength and ductility.*

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## Common Engg. Material Properties

- **Strength:**
- *Ability of a material to resist deformation.*
- *Usually considered based on maximum load that can be borne before failure is apparent.*
- *The yield strength with a safety factor is usually used.*

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## Common Engg. Material Properties

- **Hardness:**
- Resistance of a metal to plastic deformation, usually by indentation.
- May also refer to resistance to scratching, abrasion, or cutting.
- Property of a metal which gives it the ability to resist being permanently deformed (bent, broken, or have its shape changed), when a load is applied.
- Greater the hardness, greater is the resistance to deformation

## Typical failure mechanisms

- » *Fracture*
- » *Fatigue*
- » *Creep*
- » *Rupture*
- » *Corrosion*

## Fracture

- **Separation of a body into two or more pieces**
  - *in response to an imposed stress that is static (i.e. constant or slowly changing with time)*
  - *at temperatures that are low relative to the melting temperature of the material.*

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## Fracture

- *The applied static stress may be*
  - Tensile
  - Compressive
  - Shear
  - Torsional
- *Fracture involves two steps in response to imposed stress:*
  - crack formation
  - crack propagation

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## Fracture

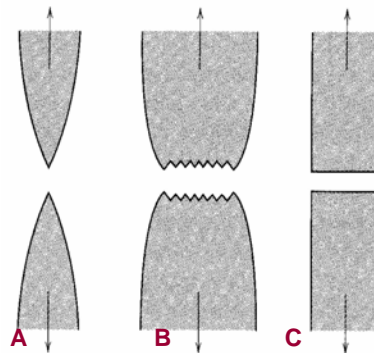
- Two possible fracture modes
  - ductile fracture
  - brittle fracture
- Mode of fracture is dependent on crack propagation.

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## Fracture Profiles

- **A** – *Highly ductile fracture in which the specimen necks down to a point.*
- **B** – *Moderately ductile fracture after necking.*
- **C** – *Brittle fracture without any plastic deformation.*



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## Ductile Fracture

- Extensive plastic deformation in the vicinity of an advancing crack.
- Relatively slow crack propagation.
- Crack is stable, i.e. resists further extension unless there is an increase in the applied stress.
- Plastic deformation gives warning of imminent fracture.

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## Brittle Fracture

- Very little appreciable deformation at the fracture surface.
- Rapid crack propagation.
- Unstable crack, i.e. crack propagation once started will continue without an increase in magnitude of the applied stress.
- Sudden and catastrophic.

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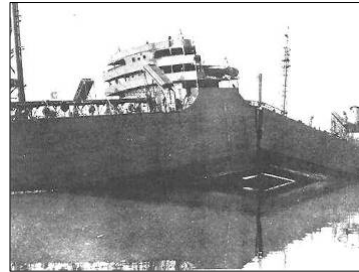


# Fatigue

- Form of failure that occurs in structures subjected to

- *Dynamic*

- *Fluctuating stresses*



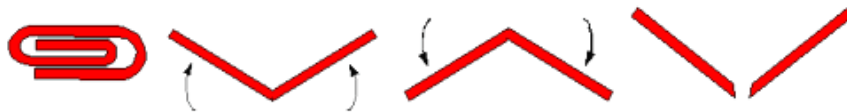
- Examples: *bridges, aircraft, and machine components.*

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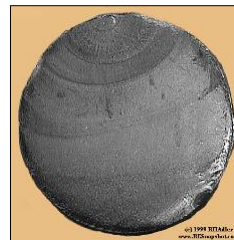
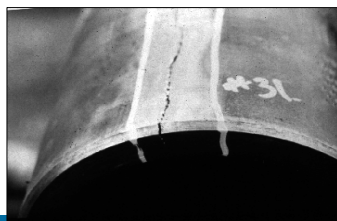
# Fatigue examples

Paper clip:



Shaft:

Petrochemical pipe:



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## Fatigue examples



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## Interesting history

- ▣ In World War II, the USA built 2708 “Liberty Ships” which were all-welded.
- ▣ 1031 failed due to brittle fracture of welded joints.
- ▣ More than 200 sunk.
- ▣ Most expensive experiment of century.
- ▣ Cause
  - ▣ steel becomes more brittle at low temperatures.
  - ▣ stress concentration at weld.

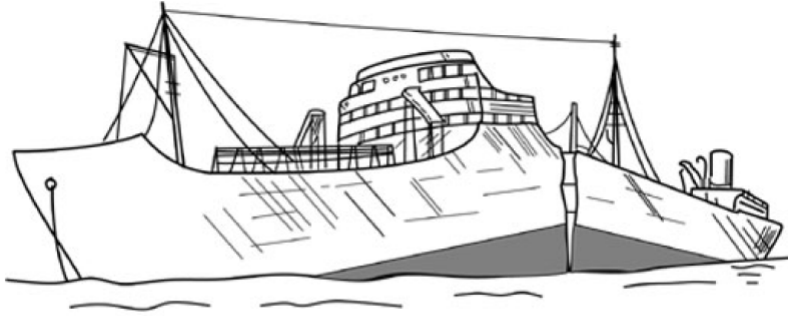


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## Interesting history

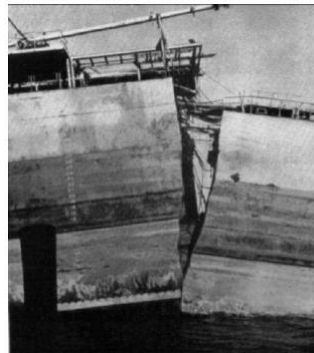


Cargo vessel "Schenectady" which suffered catastrophic failure in calm harbor.

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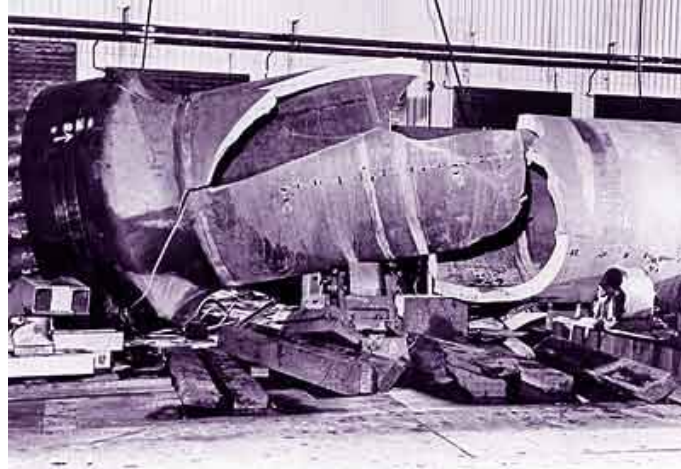
## Interesting history



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## Type of fracture?



**A) ductile fracture    B) brittle fracture**

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## Type of fracture?



**A) ductile fracture    B) brittle fracture**

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## Common Engg. Material Properties

- **Creep strength**

- *Ability of a metal to resist slow deformation due to stress.*
- *Material type, stress, temp.& environment determine its nature.*

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## Creep

- Time-dependent permanent deformation that occurs under stress.
- For most metals, it is important only at elevated temperatures.
- *Boilers, gas turbines & ovens are examples of systems having components that experience creep.*

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## Creep

- Failures are usually easy to identify due to the deformation that occurs.
- Failures may appear ductile or brittle.
- Creep testing is done at constant temperature and constant load.
- However, actual components may experience damage at various temp. and loading conditions.

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## Common Engg. Material Properties

- **Corrosion:**
  - *Process by which the metal is subjected to degradation &*
  - *subsequent deterioration in metal properties as a result of*
  - *chemical & electrical reaction with other materials.*

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## Corrosion

- Caused by the flow of electrons from one metal to another

or

- from one part of the surface of one metal to another part of the surface of the same metal.

Two basic types:

1. Uniform corrosion
2. Localised corrosion

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## General Corrosion

- Electrochemical reactions occur at approximately the same rate over the entire surface.
- Uniform rate of metal thickness loss over the surface.
- Parameters affecting general corrosion:
  - low pH, dissolved oxygen, dissolved carbon dioxide, high temperature

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## General Corrosion



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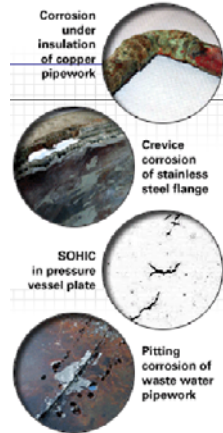
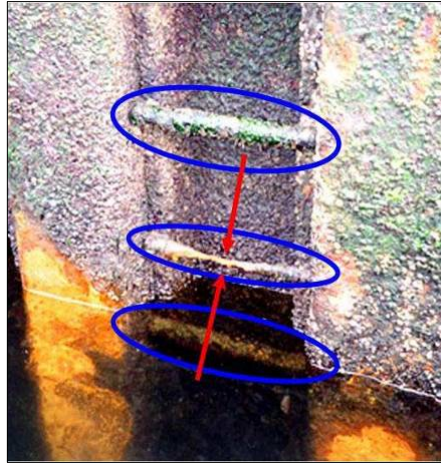
## Localized Corrosion

- Selective attack at heterogeneous site of the metal.
- Non-uniform metal thickness loss over the surface.
- Parameters affecting localized corrosion –
  - environment ( $CO_2$ ,  $C_{Cl^-}$ , pH, flow rate), material (segregation, inclusions, different phases, grain boundaries), stress (static/fluctuating)

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## Localized Corrosion



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## Localized Corrosion



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## Galvanic Corrosion

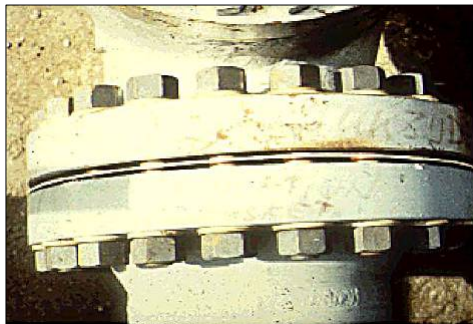


Galvanic corrosion is an electrochemical action of two dissimilar metals in the presence of an electrolyte and an electron conductive path. It occurs when dissimilar metals are in contact.

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## Crevice Corrosion



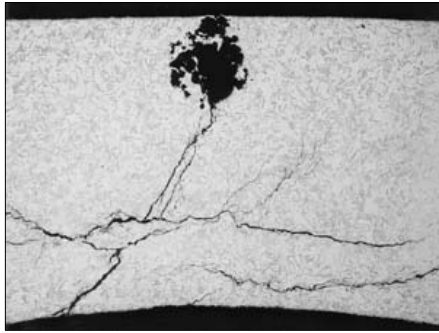
Crevice or contact corrosion is the corrosion produced at the region of contact of metals with metals or metals with nonmetals. It may occur at washers, under barnacles, at sand grains, under applied protective films, and at pockets formed by threaded joints.

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## Stress Corrosion



Stress corrosion cracking (SCC) is caused by the simultaneous effects of tensile stress and a specific corrosive environment. Stresses may be due to applied loads, residual stresses from the manufacturing process, or a combination of both.

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## Fatigue Corrosion



Corrosion fatigue is a special case of stress corrosion caused by the combined effects of cyclic stress and corrosion. No metal is immune from some reduction of its resistance to cyclic stressing if the metal is in a corrosive environment.

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## Concrete Corrosion



Concrete is a widely-used structural material that is frequently reinforced with carbon steel reinforcing rods, post-tensioning cable or prestressing wires. The steel is necessary to maintain the strength of the structure, but it is subject to corrosion.

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## Mechanical Vibrations

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- *Single degree of freedom system*
- *Terminologies: Amplitude, phase and frequency*
- *Natural frequency of vibration*
- *Multiple degree of freedom system*
- *Vibration measurement: Sensors, analyzers and interpretation*
- *Use of vibration as a condition monitoring tool*

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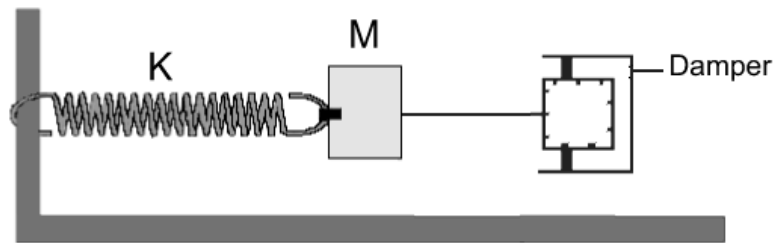
## Vibration

- Vibration is the displacement of mass back and forth from its static position during a motion of any machine or its part.
- If all the parts of the body move together in the same direction at any point in time, it is called *rigid body motion* (hence not vibration).

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## Single degree of freedom



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## Three Fundamental Properties of a Machine

- Mass ( $M$ )
- Stiffness ( $k$ )
- Damping ( $C$ )

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## Mass

- Mass is a measure of inertia of the body, which has a tendency to remain in its state of rest or motion unless an external force is applied to alter the state of the body at rest, or change the speed or direction of a moving body.
- The unit of mass is kilogram.

## Stiffness

- Stiffness can be termed as the ability of a body or structure to resist any deformation.
- It is defined as the ratio of constant force applied on a body to the displacement produced by it.
- The unit for measuring the stiffness is N/m.

## Damping

- When a machine part is set to vibrate, the velocity of the part tends to reduce under the effect of friction. Unless the force is supplied during each cycle, the velocity falls off at each successive oscillation → damping.
- The unit for measuring damping is N/(m/s).

## Three Fundamental Properties of a Machine (contd)

- All machines exhibit the three fundamental properties that determine how the machine or part responds to forces that cause vibrations.
- These properties may help reduce the vibration of a machine when it tends to vibrate excessively.

## Terminology Describing Vibration

- **Frequency**
- **Maximum deflection or amplitude**
- **Phase**

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## Frequency

- Frequency is denoted by the number of cycles passing any point in a medium per second.
- Frequency of the sine curve is the reciprocal of the curve's period.
- Frequency is measured in Hertz (Hz).

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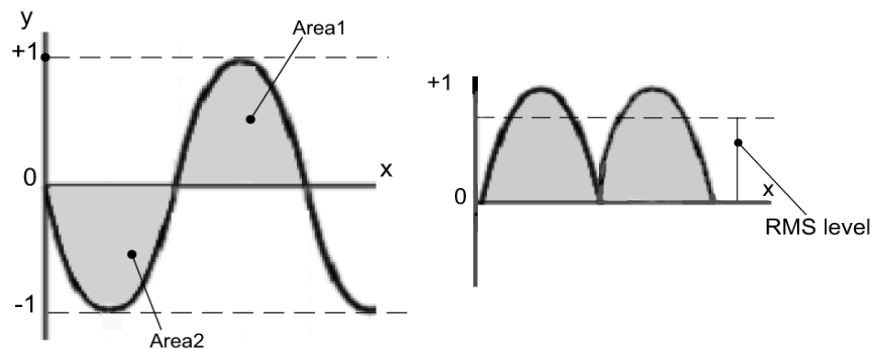
## Maximum Deflection or Amplitude

- The maximum displacement of the vibrating particle from the mean position is known as amplitude.
- The amplitude of a wave gives a relative indication of the amount of energy the wave transmits.
- Amplitude can be described in terms of the maximum, or the root mean square (rms).

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## Amplitude Description



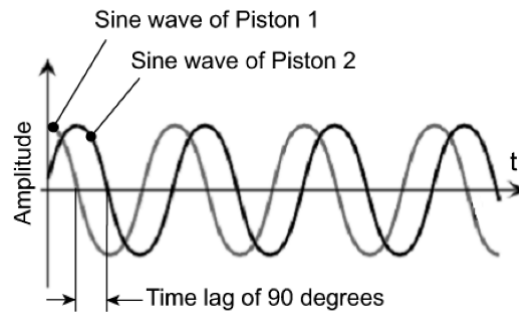
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## Phase

- Phase is described in terms of angle or fraction of time period elapsed since the particle left the mean position in the positive direction of the motion.



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## Forcing Frequency

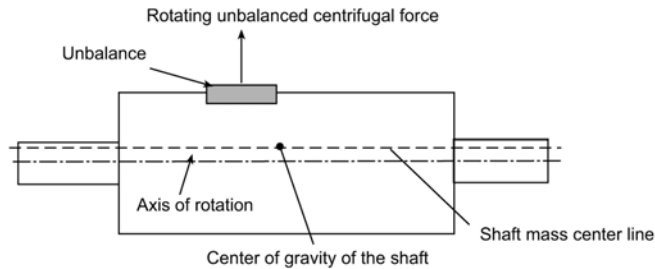
- Forcing frequencies: Produced as different events take place in a piece of machinery while its shaft completes one revolution.
- They occur when the machinery is operating, and change in magnitude in proportion to the speed of the machinery.

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## Rotational Frequency

- Rotational frequencies are caused due to residual unbalance, which causes a shift in the centre of gravity from the geometric centre of the shaft.
- This unbalance force is proportional to the momentum caused by the unbalanced mass and the square of the speed'



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## Natural Frequency

- Natural frequency: Also known as free vibration of a mechanical structure, which continues to oscillate even after excitation force is removed.
- Oscillation stops gradually due to damping in the system.
- The natural frequencies are inherent to the structure due to its mass, stiffness and damping properties.

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## Natural Frequency (contd..)

- Natural frequency depends on mass, stiffness and damping of the machinery – not on operational conditions!
- Equation given below represents the relation between natural frequency and stiffness and mass of the structure when there is no damping.

$$F_n = \frac{1}{2\pi} \sqrt{\frac{k}{M}}$$

where:

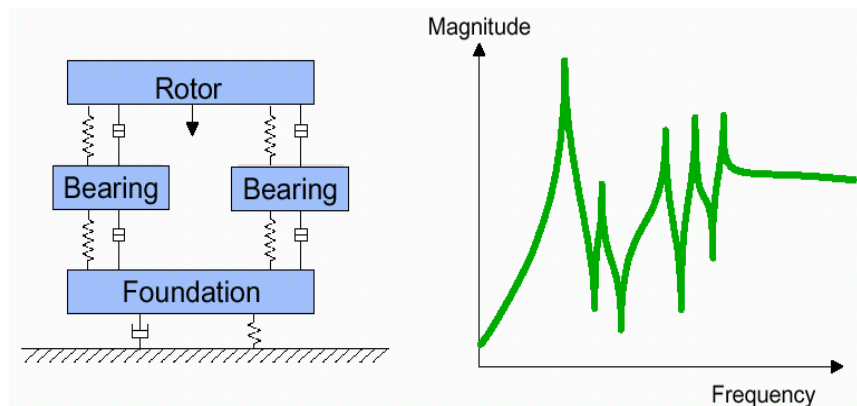
$F_n$  = natural frequency [Hz]

$k$  = the stiffness of the spring [N/m]

$M$  = mass [kg]

- Natural frequency of a system is usually expressed in Hertz [Hz].

## Multiple degree of freedom



## Vibration Measurement

### Sensor / transducer

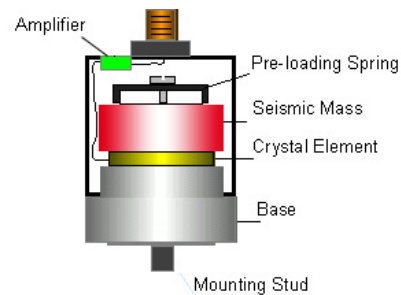
- Converts one energy type (vibration) into another (voltage / electric current)
- Measures machinery / structural vibrations
- Includes velocity pickups, accelerometers, proximity probes

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## Vibration Measurement

- **Accelerometers**
- Most commonly used
- Light, compact and quite rugged while also possessing a wide frequency range.



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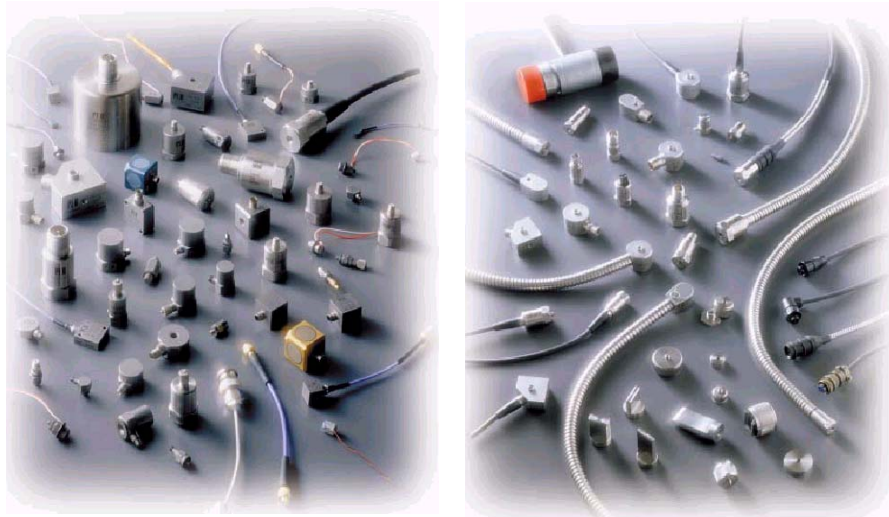
## Vibration Measurement

- Accelerometers utilize piezoelectric principle to convert mechanical motion into a voltage signal proportional to acceleration of the vibration.
- Consist of a piezoelectric crystal made of ferroelectric materials and a small mass enclosed in a protective metal case.

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## Accelerometers



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## Vibration Measurement

Which to choose:

- Vibration severity: Measure of displacement, velocity or acceleration characteristics of vibration.
- Can look at spectrum or overall vibration.
- Greater vibration amplitudes generally correspond to higher level of machinery faults.

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## Vibration Measurement

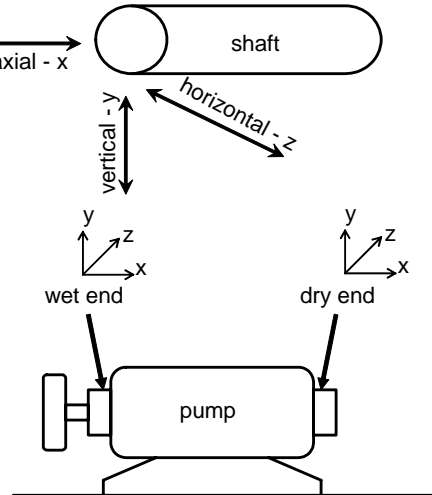
- Frequencies below 10 Hz: Vibration levels for displacement large.
- Acceleration yields significant values in high frequency range (1000 – 20 000 Hz) → choose acceleration.
- Severity of vibration best indicated by velocity in frequency range 10 – 1000Hz.

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## Vibration Measurement

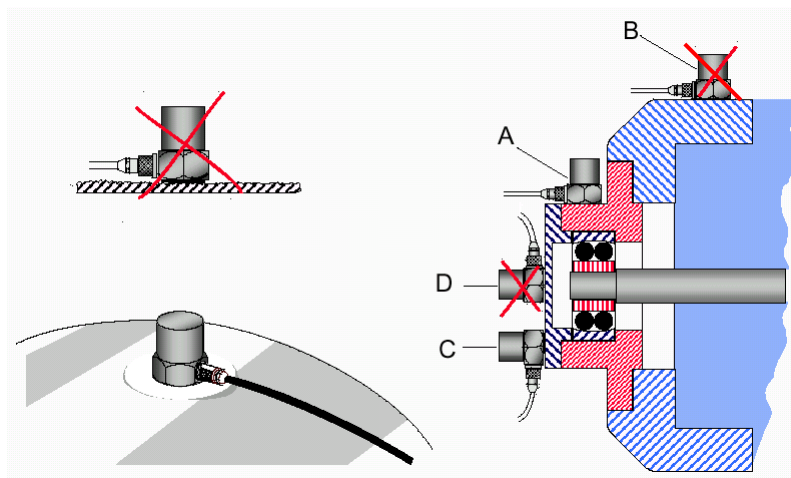
- **Sensor Mounting Precautions**
- Measurement surface should be sufficiently stiff to resist pressure exerted by the probe.
- Measure motion along major axes – V  
H A



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## Sensor mounting



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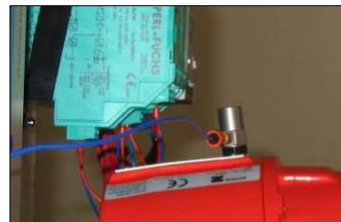
## Sensor mounting



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## Sensor mounting



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## Vibration Measurement

- **Spectrum Analyzers**
- Electronic devices that convert the time waveform of a given signal into its frequency components.
- Possible to show on-line vibration spectra, overall vibration levels, phase, balancing information, etc.



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## *Vibration Measurement*

- **Two-channel Analyzer**
- Collect, record and display vibration-related characteristics such as FFT spectra, trend plots and time domain waveforms.



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## Vibration Measurement

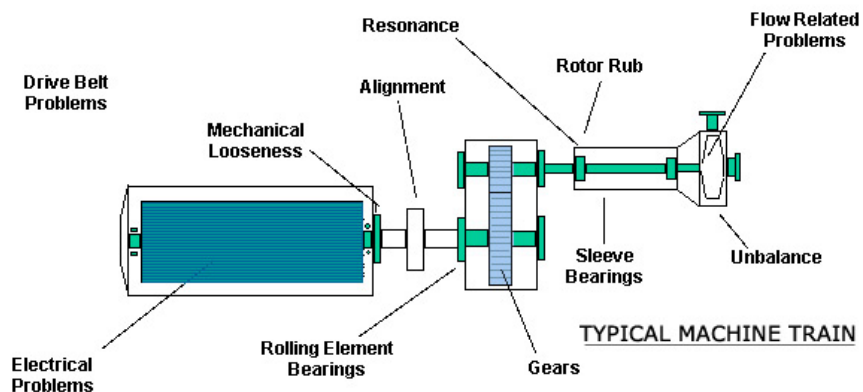
- **Handheld Vibration Meters**
- Determine the overall vibration levels in a machine and detect abnormalities in machine vibration.
- Typically battery-powered, use an accelerometer for sensing purposes.



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## Machinery Fault Detection



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## Reasons for Defects that Cause High Vibrations in Machines

- Unbalance of rotating parts
  - Machining errors
  - Rotor eccentricity
  - Uneven mass distribution in electric motor rotor windings
  - Missing balance weights
  - Bowed shafts
  - Lack of homogeneity in cast parts
  - Uneven dirt accumulation in cast parts
- Misalignment of couplings or bearings
  - Faulty assembly of subassembly parts of motors and pumps
  - Shifting of the relative position of components after assembly
  - Distortion due to forces exerted by piping
  - Distortion of flexible supports due to torque
  - Temperature induced growth of machine structure
  - Coupling face not perpendicular to the shaft axis

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## Reasons for Defects that Cause High Vibrations in Machines (contd)

- **Bent shafts**
- **Journal Bearings:**
  - oil whip, oil whirl, looseness of the journal or journal thrust bearings (all of these mostly occurs at a low frequency levels)
- **Rolling element Bearings:**
  - improper lubrication, improper mounting, misalignment, overloading and other manufacturing defects
- **Mechanical looseness:**
  - rotational and non-rotational looseness
- **Electrically induced vibration:**
  - slip related vibration, slot pass frequency or shorted laminations

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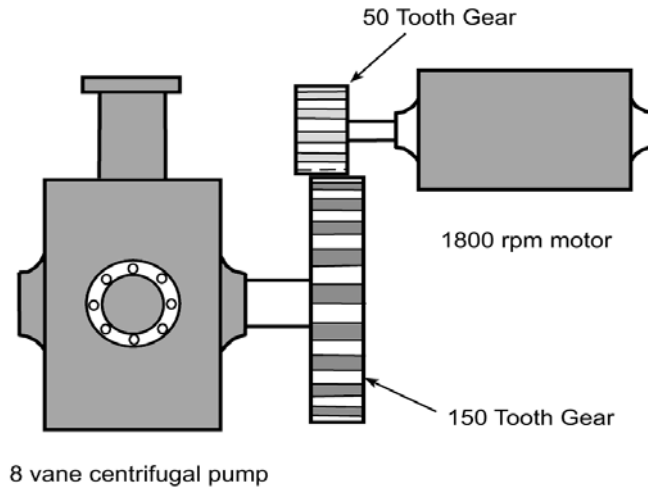
### Reasons for Defects that Cause High Vibrations in Machines (contd)

- **Others:**
  - Combustion noise in turbines
  - Suction pressure, discharge pressure and cavitation will affect the vibration signature.
  - Uneven build-up of waste particles in axial or centrifugal fans
  - Damaged or eroded vanes of centrifugal compressors
  - Drive belt defects such as:
    - mismatched, worn or overstretched belts
    - eccentric or misaligned sheaves or sheave run-outs in belts
    - Belt resonance
  - Defects in gearboxes such as
    - Gear hunting
    - Machining errors of the teeth
    - Damaged gear teeth
    - Eccentric gears and bent shafts

### Vibration as a condition monitoring tool

- Frequency analysis is also known as spectrum analysis.
- Frequency analysis is done by transforming the information in the signal from the time domain into the frequency domain.
- Frequency analysis is usually performed when the time domain waveform cannot clearly represent the spectrum.

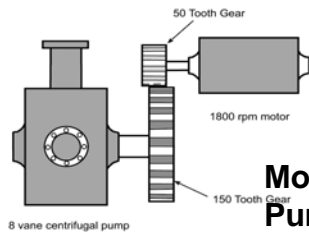
## A Typical Mechanical System



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## A Typical Mechanical System



**Motor frequency =  $1800/60 \text{ rpm} = 30 \text{ Hz}$**

**Pump frequency =  $50/150 \times 1800 \text{ rpm}$   
 $= 600 \text{ rpm} = 10 \text{ Hz}$**

**Gear mesh frequency =  $50 \text{ teeth} \times 1800 \text{ rpm}$   
 $= 150 \text{ teeth} \times 600 \text{ rpm}$   
 $= 90\,000 \text{ rpm}$   
 $= 1500 \text{ Hz}$**

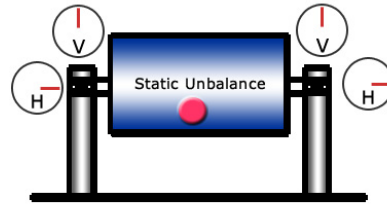
**Blade frequency =  $8 \text{ vanes} \times 600 \text{ rpm}$   
 $= 4800 \text{ rpm}$   
 $= 80 \text{ Hz}$**

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## Unbalance – Static

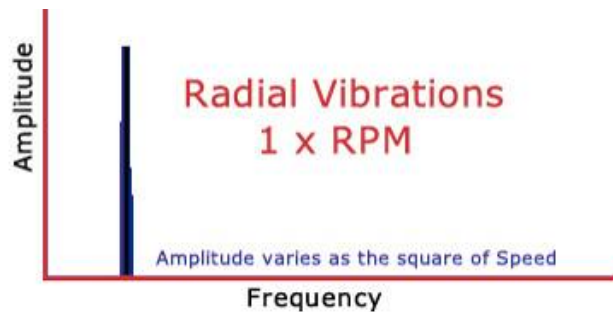
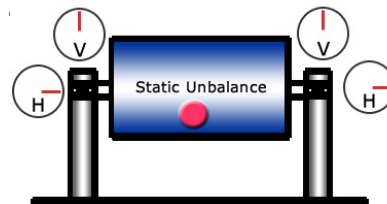
- Amplitude due to unbalance will vary with the square of speed.
- The FFT will show  $1 \times \text{rpm}$  frequency of vibration.
- It will be predominant.
- Phase difference is as shown.



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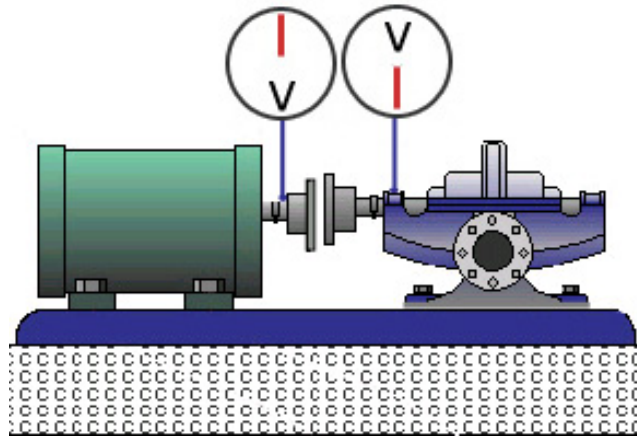
## Unbalance



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## Parallel Misalignment

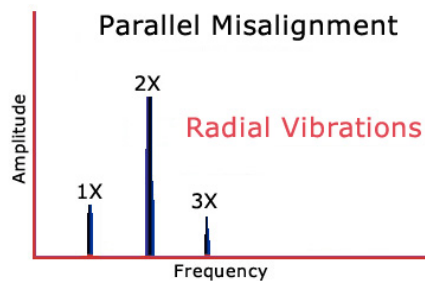


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## Parallel Misalignment

- The predominant peak is at 2x.
- Vibrations in radial direction are higher than in the axial direction.



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