# Machine Condition Monitoring

# and

# Fault Diagnostics

**Chris K Mechefske**

# Current Topic

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Type
- Automatic Diagnostic Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods

# Fault Diagnostics Based on Machine Type

Pumps

Electric Motors

Compressors

Fans

Steam / Gas Turbines

Reciprocating Machines

# Centrifugal and Axial Machines

- Pumps, fans and compressors
- Pumps and fans transport fluids by converting mechanical work into energy of the fluid in the form of pressure and velocity
- Compressors increase the energy of the compressed fluid as pressure
- The flow can be radial (centrifugal) or axial
- Pumps work with liquid fluid while fans and compressors work with gas

# Pumps

- The vibration spectra of these machines are characterised by a peak at the
  - Blade Pass Frequency (BPF)
  - Vane Pass Frequency (VPF)

To calculate these frequencies:
BPF (Blade Pass Frequency) = No. of Blades x rpm
VPF (Blade Pass Frequency) = No. of Vanes x rpm

# Pumps

## Some Background

- pumps move fluid from one point to another by adding energy
- the energy added is measured as head rather than pressure (independent of fluid specific gravity)
- total work done by a pump is called system head
- System head: - static head
  - friction head
  - velocity head

# Pumps

## Static head

- difference in elevation between suction and discharge
- measured between fluid levels or from pump centre line
- static discharge head
- static suction head (to prevent cavitation)

# Pumps

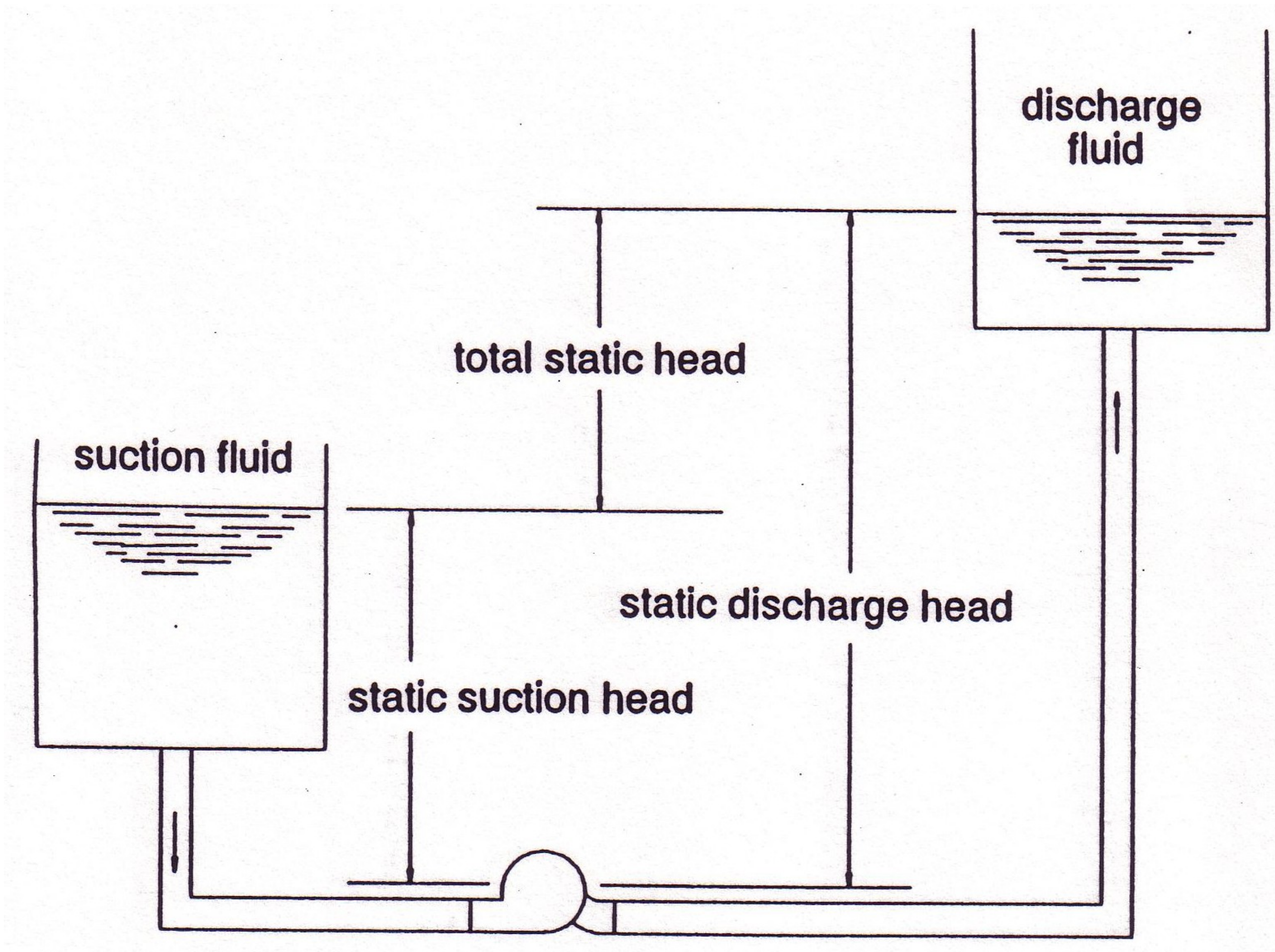
## Friction head

- head required to overcome friction losses
- varies with quantity of flow, pipe size, components in system, fluid type

## Velocity head

- kinetic energy of the fluid
- equal to the distance the fluid mass would have to fall to obtain the same velocity

# Pumps



discharge fluid
total static head
suction fluid
static discharge head
static suction head

# Pumps

## Types of Pumps

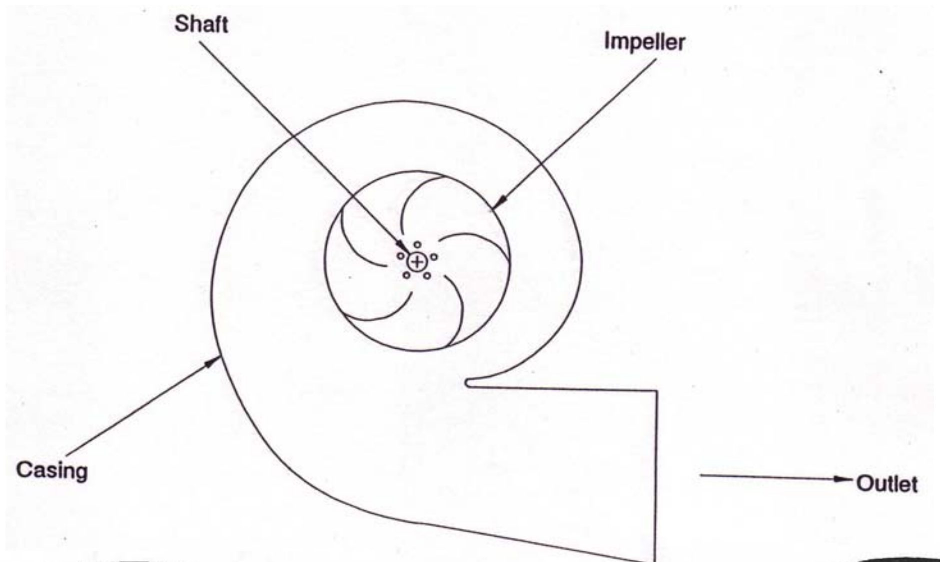
- Centrifugal
- Axial

## Centrifugal

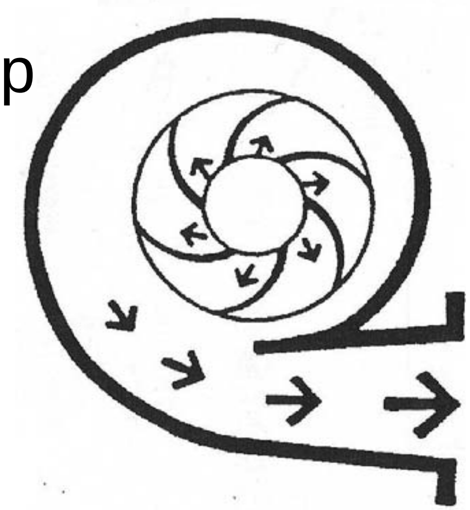
- suction created at inlet.
- one impeller - single stage
- several impellers in series - multi stage
- pumps provide head with both pressure and velocity components

# Pumps

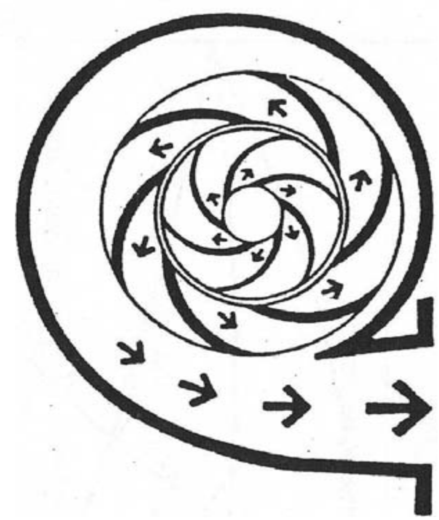
## Basic Centrifugal Pump




Volute Pump



Diffuser Pump



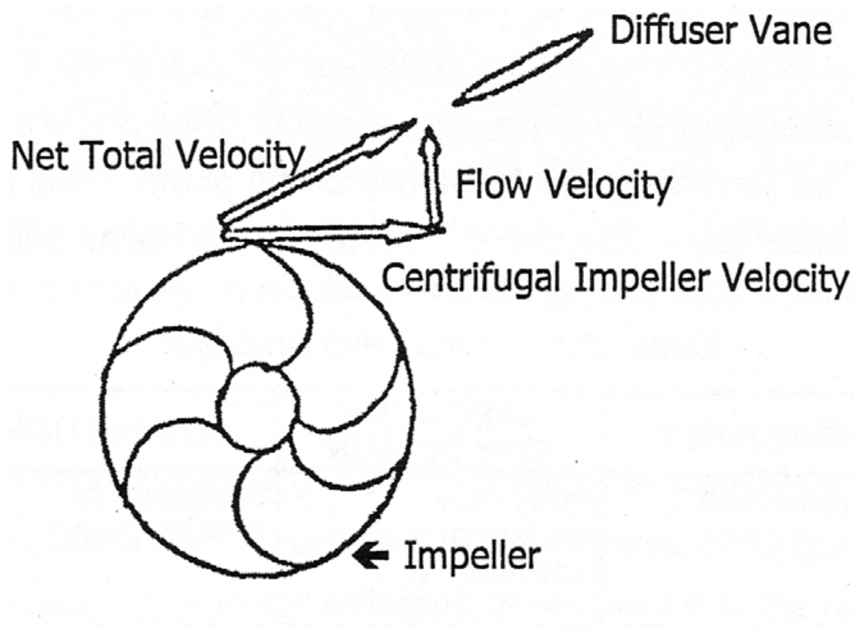
# Pumps

## To convert velocity to pressure:

- use a volute (ever widening pump casing)
- 360° curve
- with pump working at or near design capacity there is uniform pressure on the impeller (below design capacity results in unequal forces on impeller and therefore a net radial movement of the impeller)
- design with heavier shaft & bearings
- include a twin volute, 180° curve (unequal pressures acting in opposite directions)
- diffusion vanes (stationary vanes surrounding pump impeller)

# Pumps

## Flow path characteristics

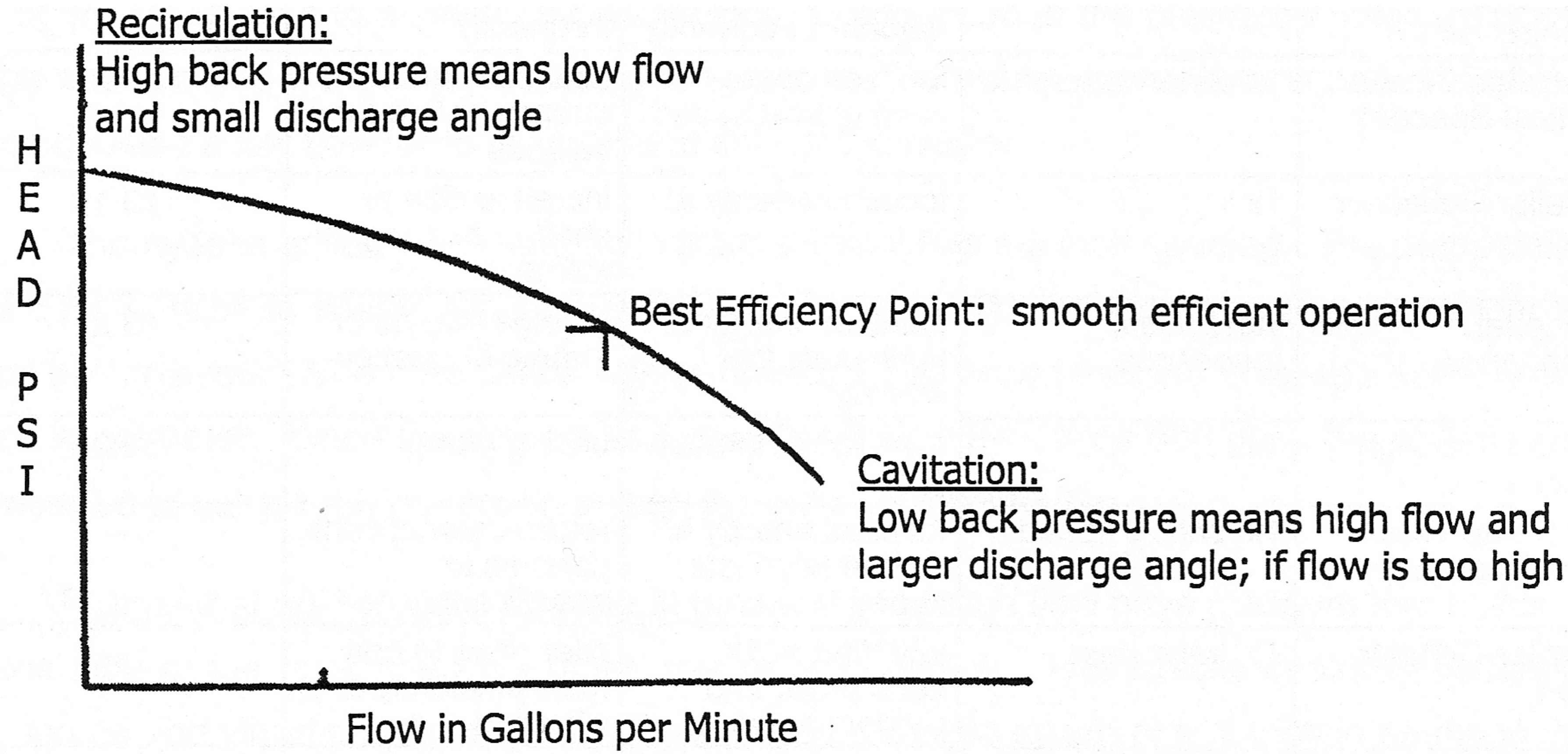



At best efficiency design point, fluid discharge angle matches angle of diffuser and flow is smooth with minimal disturbances.

If flow is decreased (too much back pressure) or is increased (too little back pressure), the fluid flow angle no longer matches the design flow angle, resulting in higher vibration and loss of efficiency.

# Pumps

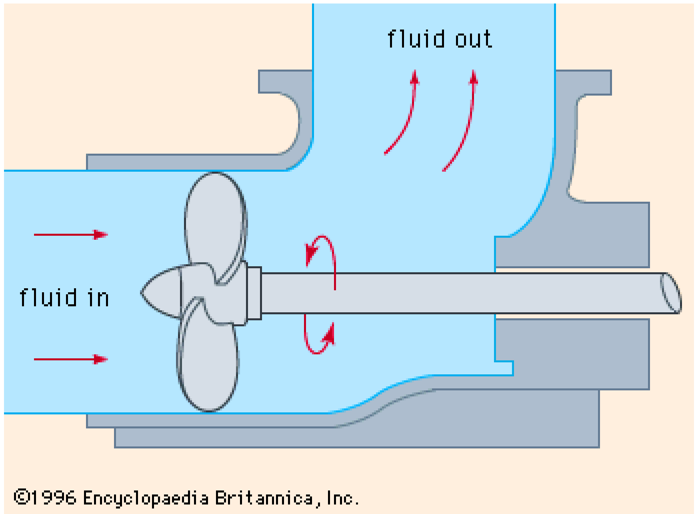
## Pump flow versus head curve



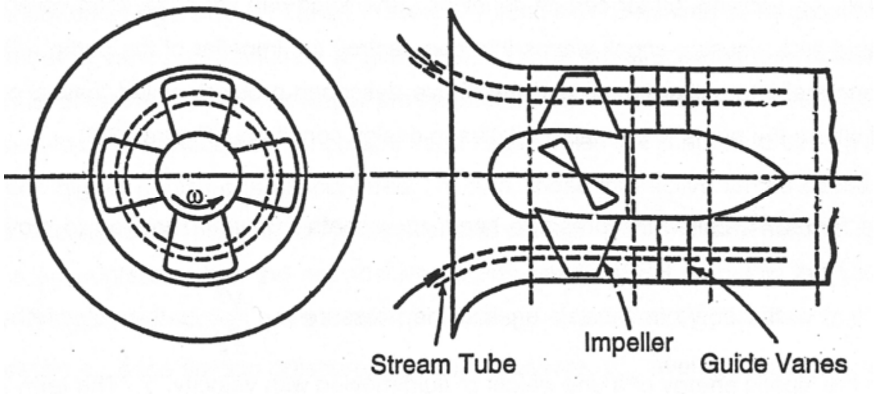

As back pressure is decreased, flow through the pump increases, and fluid discharge angle increases

# Pumps

## Axial Flow Pumps







# Pumps

## Pump spectra for specific conditions: Normal

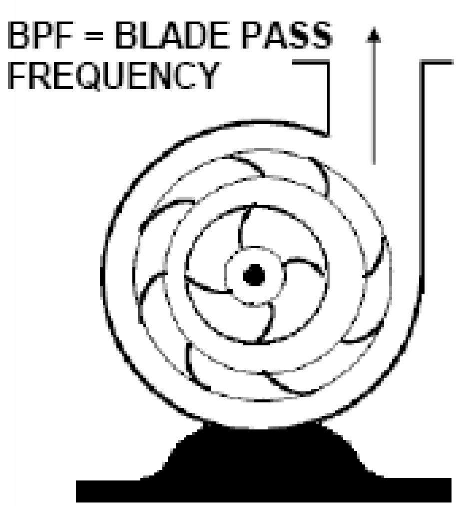
*Blade Pass and Vane Pass*

➢ Blade Pass Frequency (BPF) = number of blades (or vanes) x RPM

➢ This frequency is inherent in pumps, fans and compressors and normally does not present a problem

➢ Large amplitude BPF (and harmonics) can be generated in the pump if the gap between the rotating vanes and the stationary diffusers is not kept equal all the way round.

➢BPF (or harmonics) sometimes coincide with a system natural frequency causing high vibration

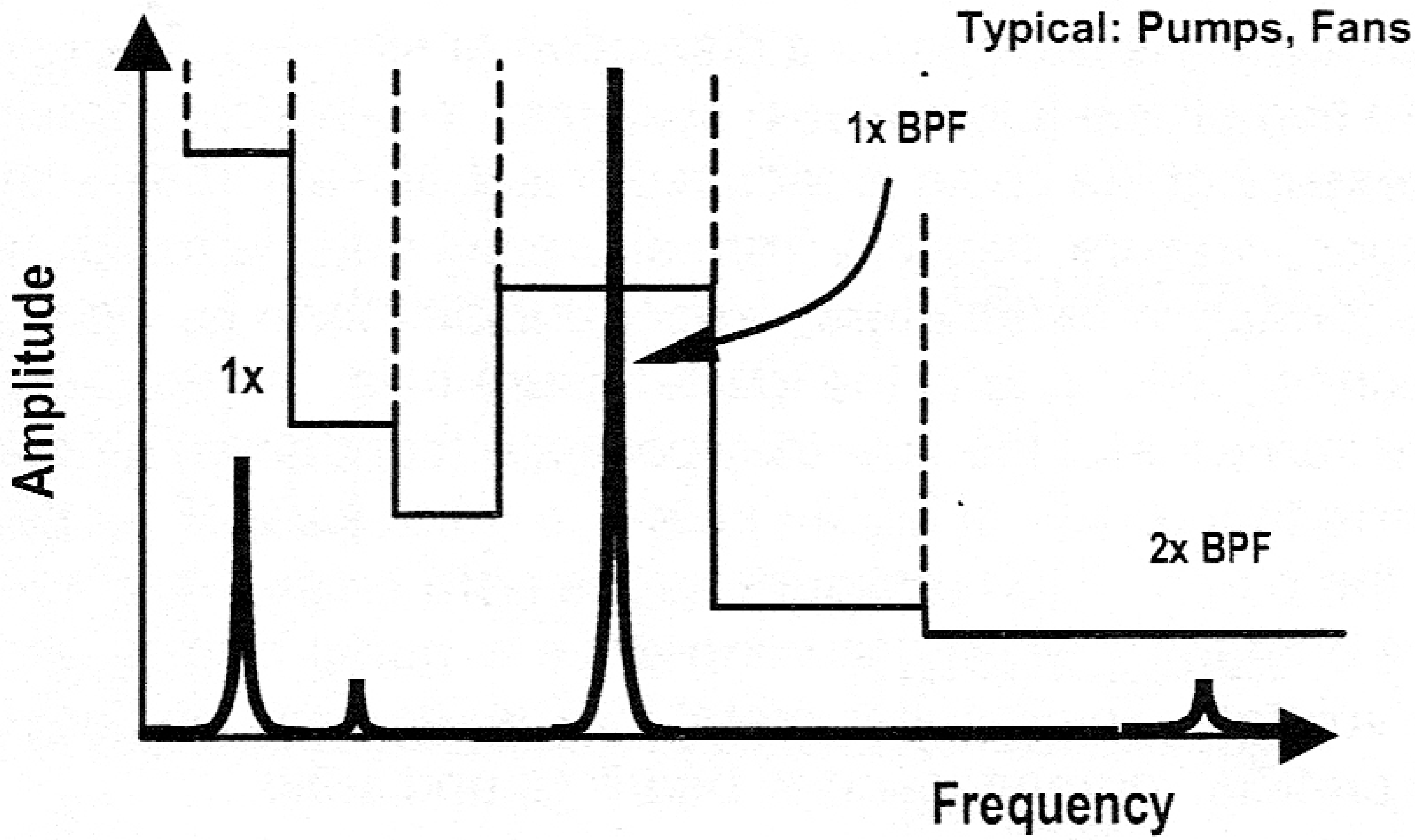



➢ High BPF can be generated if the wear ring seizes on the shaft or if welds fastening diffusers fail

➢High BPF can be caused by abrupt bends in linework (or duct), obstructions which disturb the flow path, or if the pump or fan rotor is positioned eccentrically within the housing

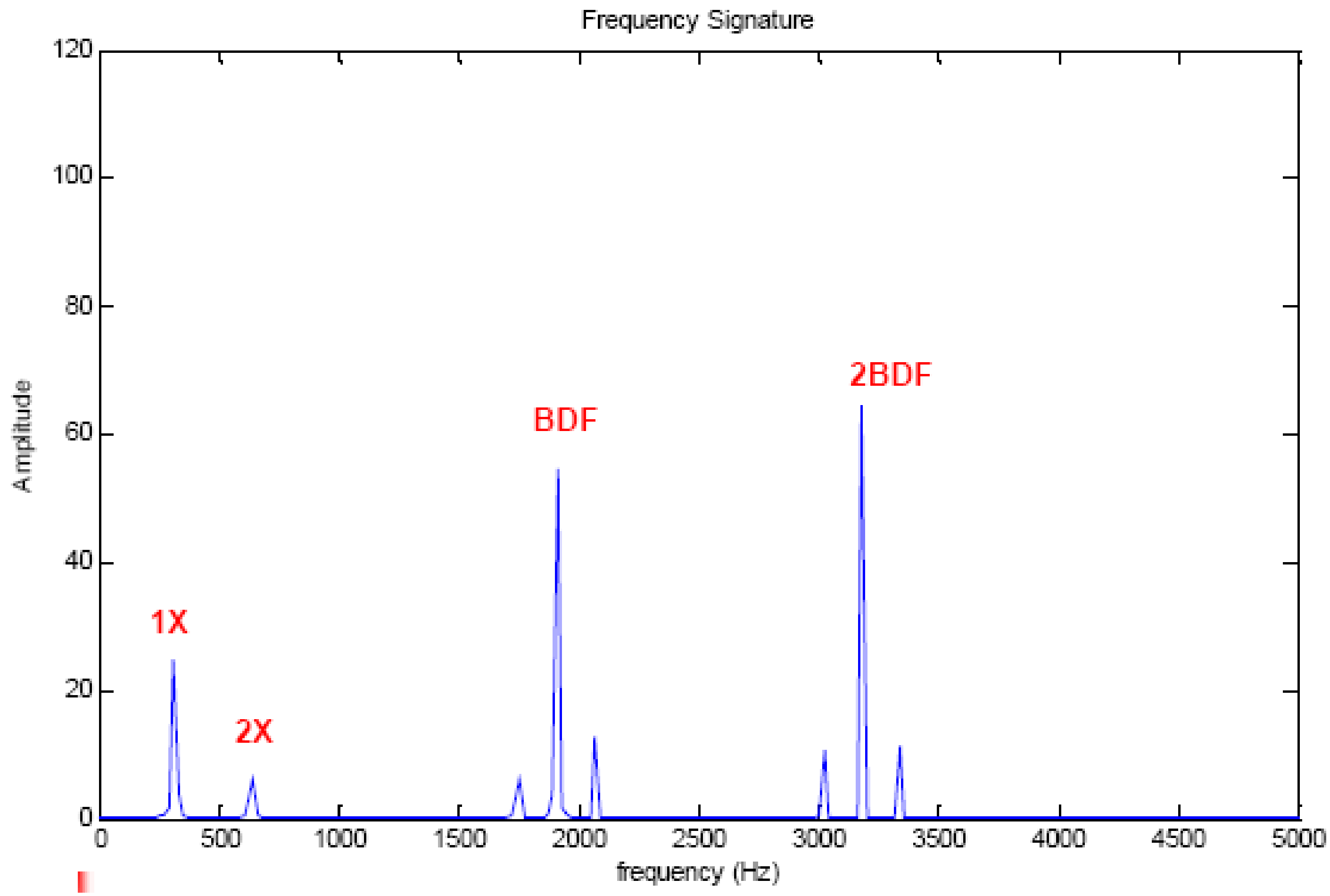
# Pumps

BLADE PASSING FREQUENCY



# Pumps

## Pump spectra for specific conditions: Normal

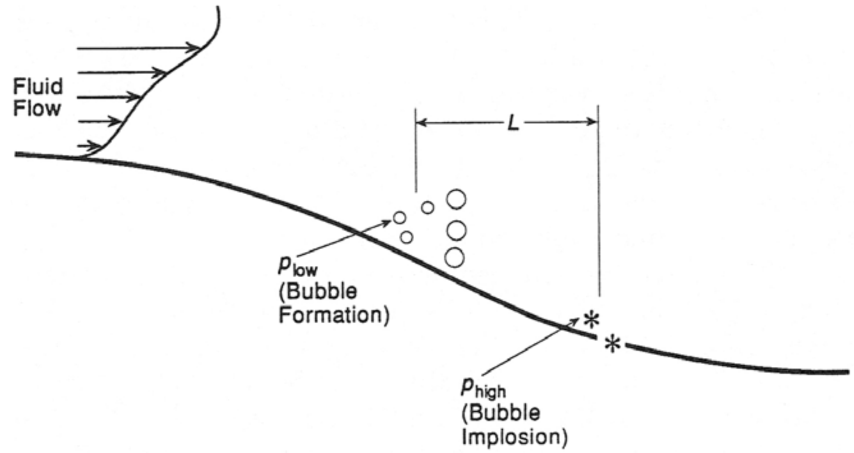


# Pumps: Sources of vibration

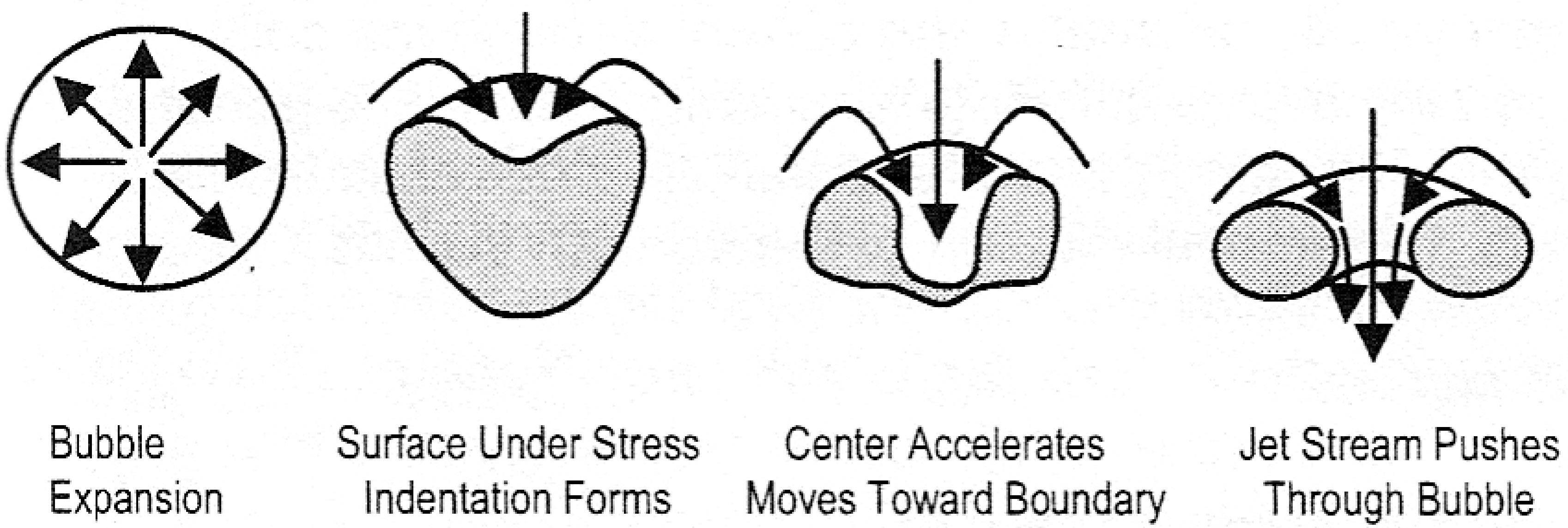
- Hydraulic: Cavitation
  - phenomenon where small and largely empty cavities are generated in a fluid, which expand to large size and then rapidly collapse, producing a sharp sound. Cavitation occurs in pumps, propellers, impellers, and hydro-electric turbines.

Source: Wikipedia

# Pumps: Sources of vibration




Cavitation Bubble Collapse Example



# Pumps: Sources of vibration

Hydraulic: Cavitation

- decrease in atmospheric pressure
- increase in fluid temperature
- increase in velocity or viscosity
- pipe obstructions, change in direction (deviation of laminar flow)
- vibration at 1 $\times$ RPM with harmonics up to blade pass frequency
- high frequency noise
- increase pressure in system to reduce cavitation

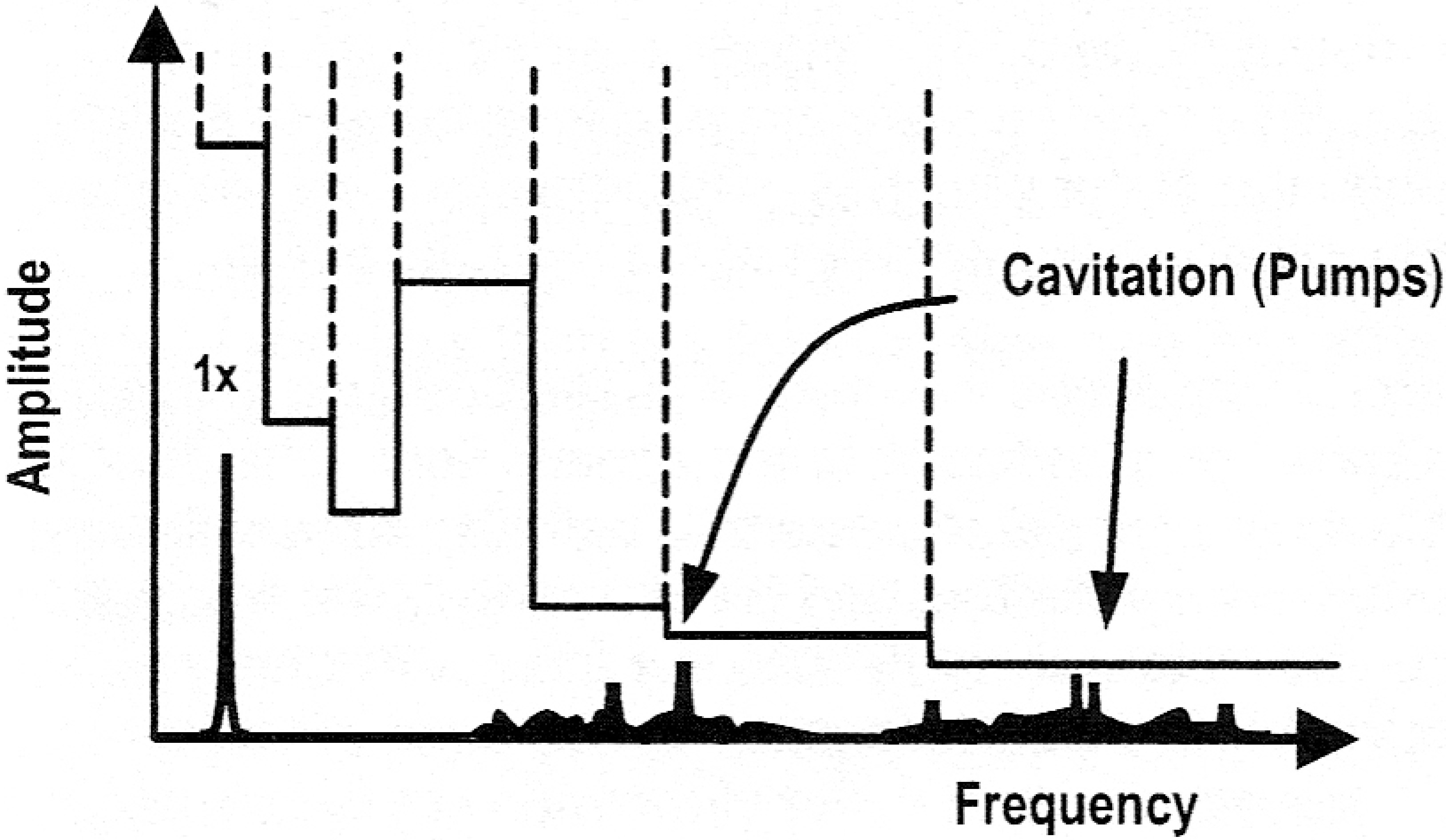
# Pumps

## Cavitation in a pump

- Cavitations normally generates random, higher frequency broadband energy which is sometimes superimposed with blade pass frequency harmonics
- Normally indicates insufficient suction pressure (starvation)
- Cavitations can be quite destructive to pump internals if left uncorrected
- It can particularly erode impeller vanes.
- When present, it often sounds as if "gravel" is passing through the pump

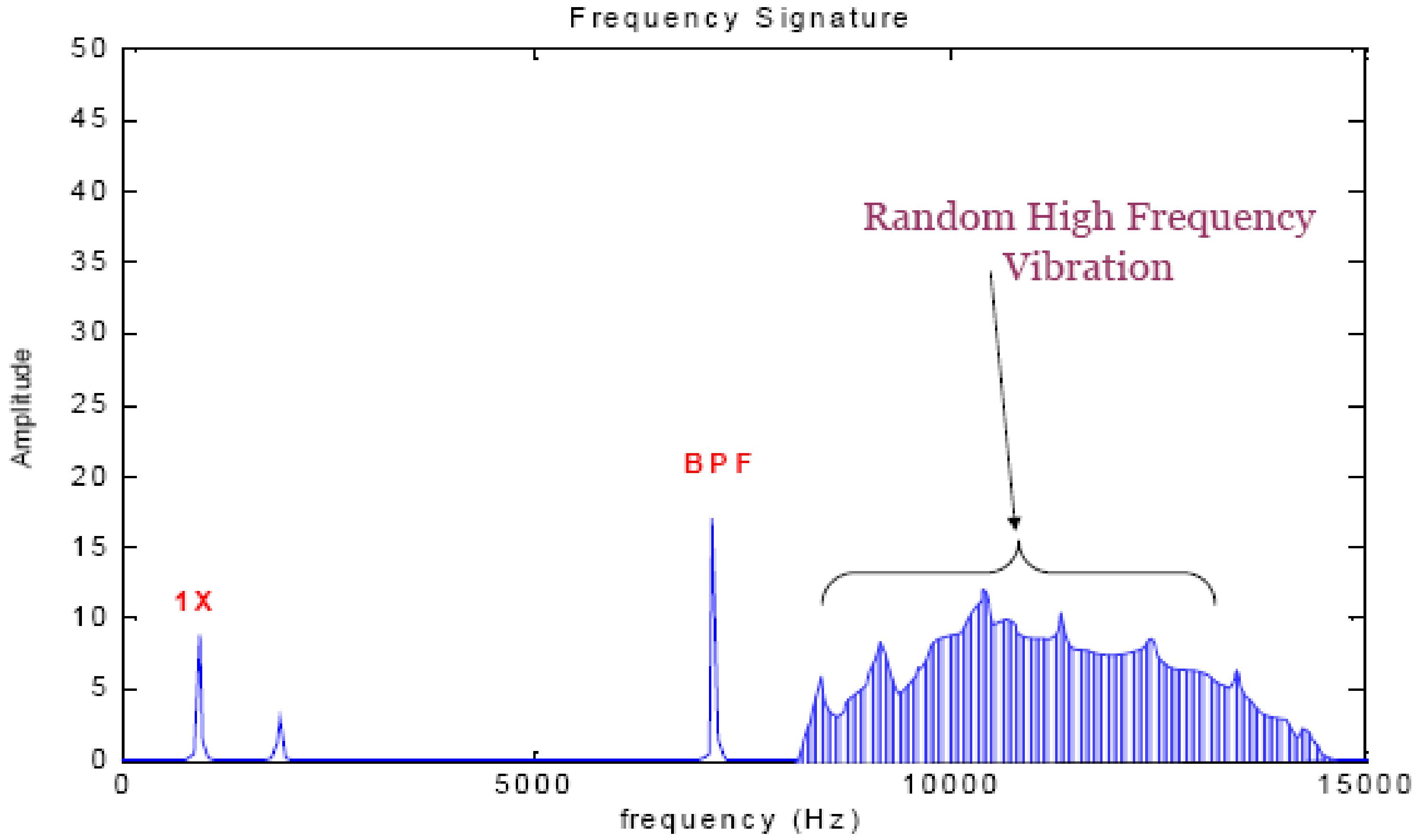
Queen's
CAVITATION

# Pumps: Sources of vibration



# Pumps

## Cavitation in a pump



# Pumps

## Recirculation

- high discharge pressure accompanied by low flow
- flow through seals, impeller clearance
- sub-harmonics of operating speed
- install a bypass

## Hydraulic unbalance

- poor design of suction piping (elbow close to inlet)
- poor impeller design (unsymmetrical)
- high 1 $\times$ RPM axial vibration

# Pumps

## Interaction with volute or diffuser

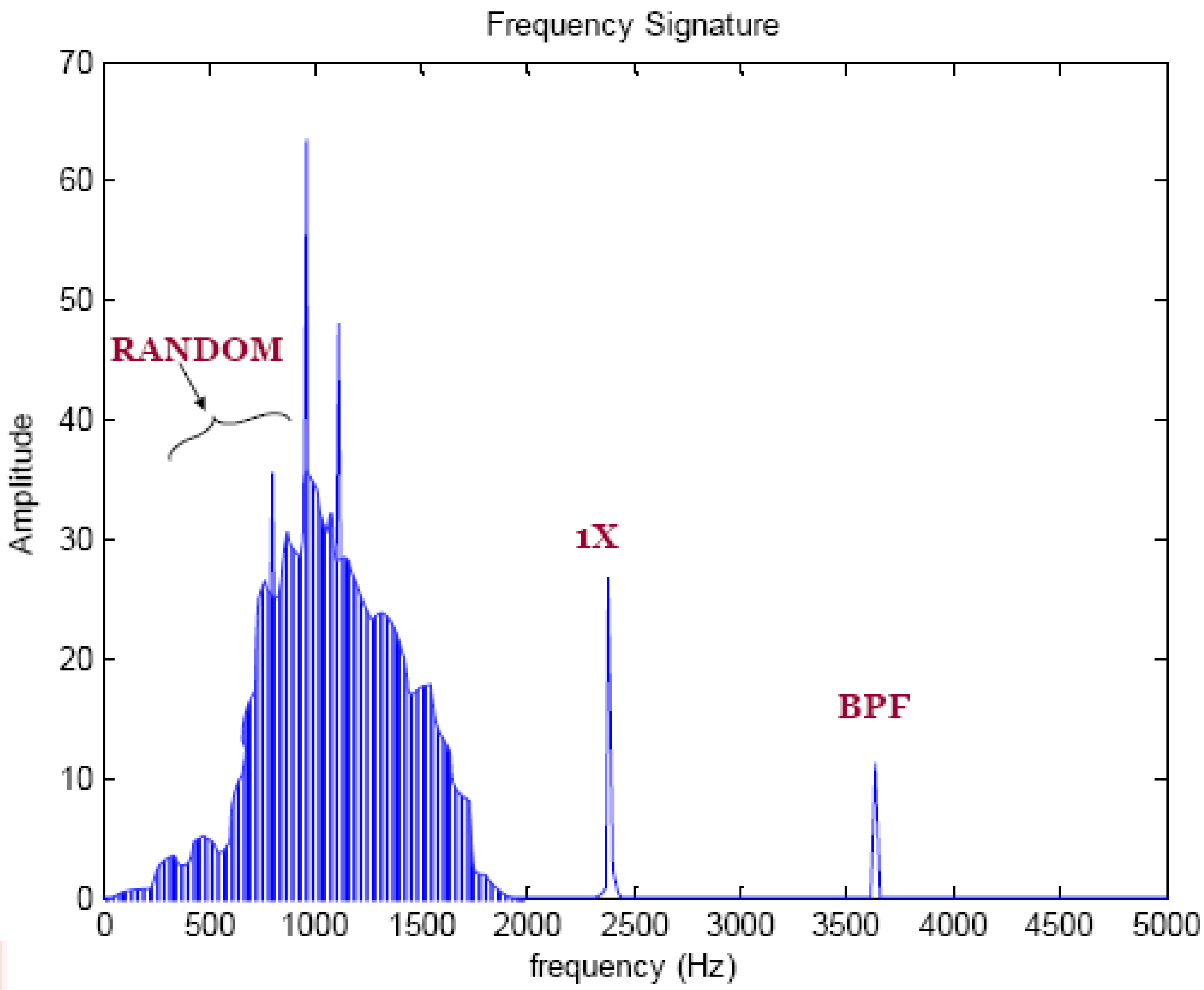
- pump operating below rated capacity
- turbulence due to fluid interacting with volute or diffusion vanes at an incorrect angle
- high sub-synchronous axial vibrations

## Misalignment

- thermal growth or high pressures may cause misalignment
- 2 $\times$ RPM vibration
- radial or axial vibration

# Pumps

## Flow turbulence in a pump



# Pumps

## Impeller unbalance

- mechanical unbalance
- high 1 $\times$ RPM vibration

## Impeller instability

- excessive clearance due to wear causes changes in impeller resonances

# Pumps

**Bent shaft**

- manufacturing defects
- pressure pulses, cavitation
- blade impacts

**Pipe stresses**

- inadequate pipe support
- stress on pump casing
- cause of misalignment

# Fault Diagnostics Based on Machine Type

## PUMPS

Common pump faults

**Critical Speeds** (mechanical resonances)
**Structural Resonances** (principally vertical pumps)
**Acoustical Resonances** (piping design)
**Impeller Eccentricity** (non-concentric machining, deflection of impeller shaft due to head)
**Impeller Unbalance**
**Impeller/Diffuser Clearance** (gaps too large or too small)
**Recirculation** (low flow)
**Cavitation** (low suction head)
**Oil Whirl** (bearing design and excessive clearance)
**Wear Ring Clearance** (modifies critical speed, may induce oil whirl)

# Fault Diagnostics Based on Machine Type

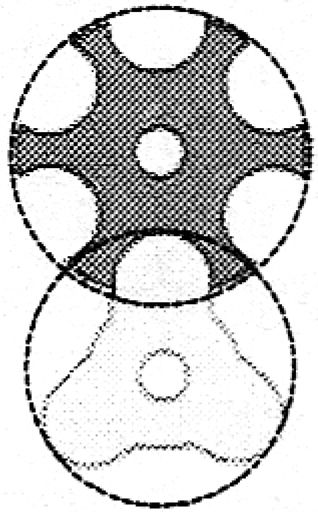
## COMPRESSORS

Compressors act in much the same way as pumps only they are compressing some type of gas

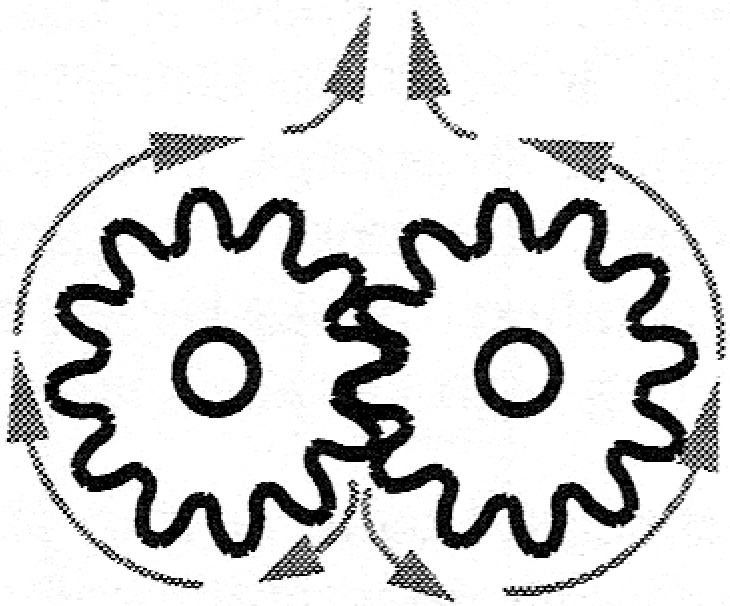
They come in many different sizes, but only two principal types; 1) screw type, and 2) reciprocating compressors

Screw type compressors have a given number of lobes or vanes on a rotor and generate a vane passing frequency

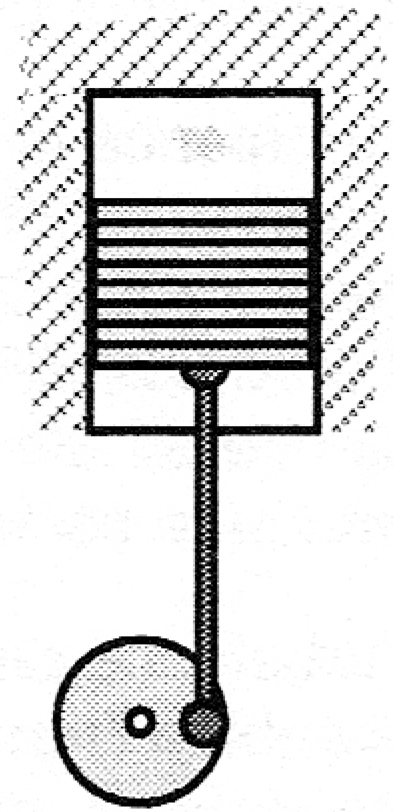
# Compressors



Lobe Type Compressors



Gear Type Pumps



Reciprocating Type Compressors

# Compressors

Screw compressors with multiple rotors can also generate strong 1X and harmonics up to vane pass frequency

The close tolerances involved result in relatively high vibration levels even when the machine is in good condition

As with pumps, signals taken from pressure transducers in the discharge line can be useful for diagnostics

# Compressors

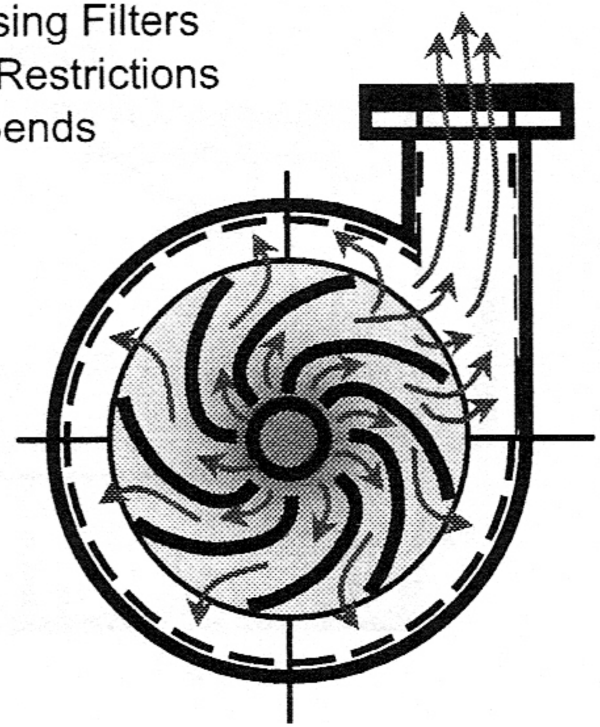
Pumps vs. Compressors

Sources of Excessive BPF include the following:

- Rotor or Housing Eccentricity
- Non-uniform Variable Pitch Blades
- Loose, Bent, or Misaligned Housing Diffuser Vane(s)
- Blade or Vane Wear (Abrasive Materials, Cavitation)
- Operation @ Improper Performance Parameters
- Improper Damper Settings in Blowers
- Dirty, Damaged, or Missing Filters
- Inlet or Discharge Line Restrictions
- Abrupt Plumbing Line Bends
- Resonance Excitation

**Also Known As:**

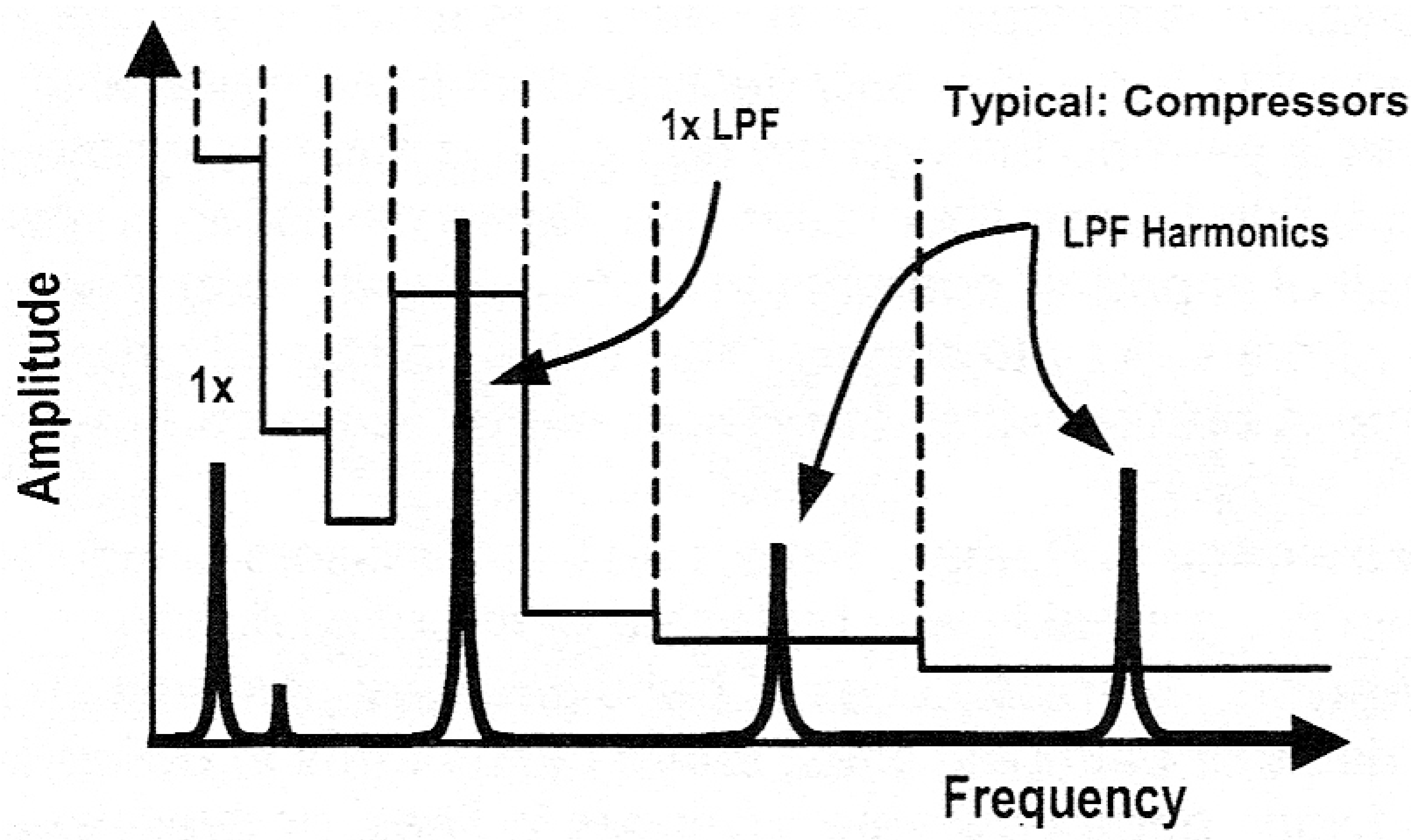
**Lobe Passing Frequency (LPF)**
**Vane Passing Frequency (VPF)**
**Piston Passing Frequency (PPF)**



# Compressors

- Most centrifugal compressors have massive casings and lightweight rotors that make seismic vibration measurements difficult
- Permanently-mounted proximity probes are preferred to measure relative rotor vibration
- Compressor faults are similar to those encountered in steam turbines and pumps
- Fault frequencies occur at or synchronous to operating speed or its multiples
- The minimum flow point is the surge limit. Operation is unstable below the surge limit

# Compressors

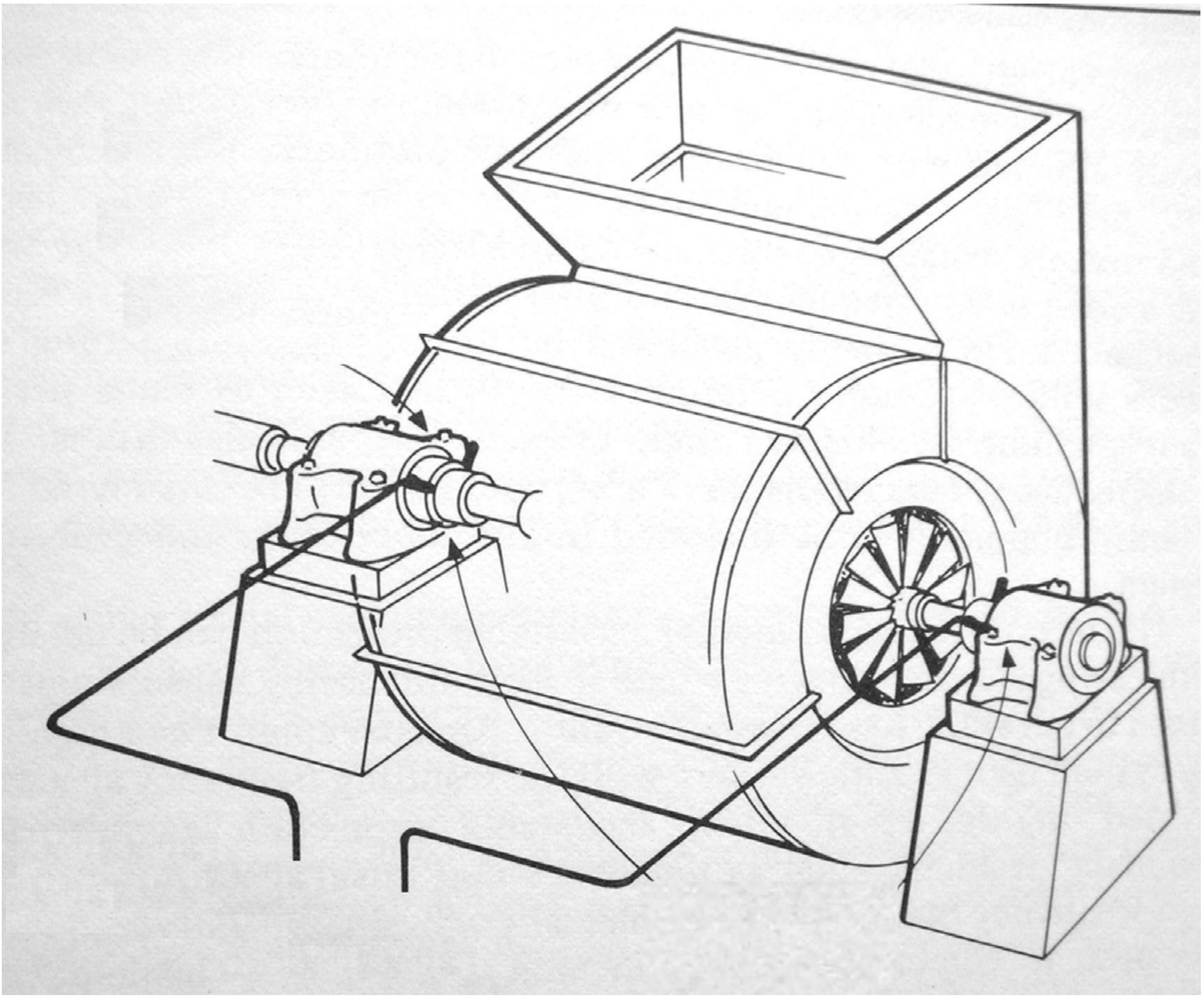


# Fault Diagnostics Based on Machine Type

## FANS

- Primary function is to move air
- Typical running speeds are 700 to 950rpm
- Rotor is usually supported on pillow blocks

# Fans



# Fans

## Axial Flow Fans

# Fans

## Some Definitions

Total fan pressure:

- the difference between the pressure at the fan inlet and the fan outlet

Fan velocity pressure:

- the pressure resulting from the average air velocity at the fan outlet

Fan static pressure:

- total fan pressure minus the fan velocity pressure

# Fans

Air power:

- the work done by the fan in moving air against a constant pressure

$$P = p \times Q$$

- where:

P = air power

p = pressure difference between the fan inlet and outlet

Q = volume of air moved per unit time

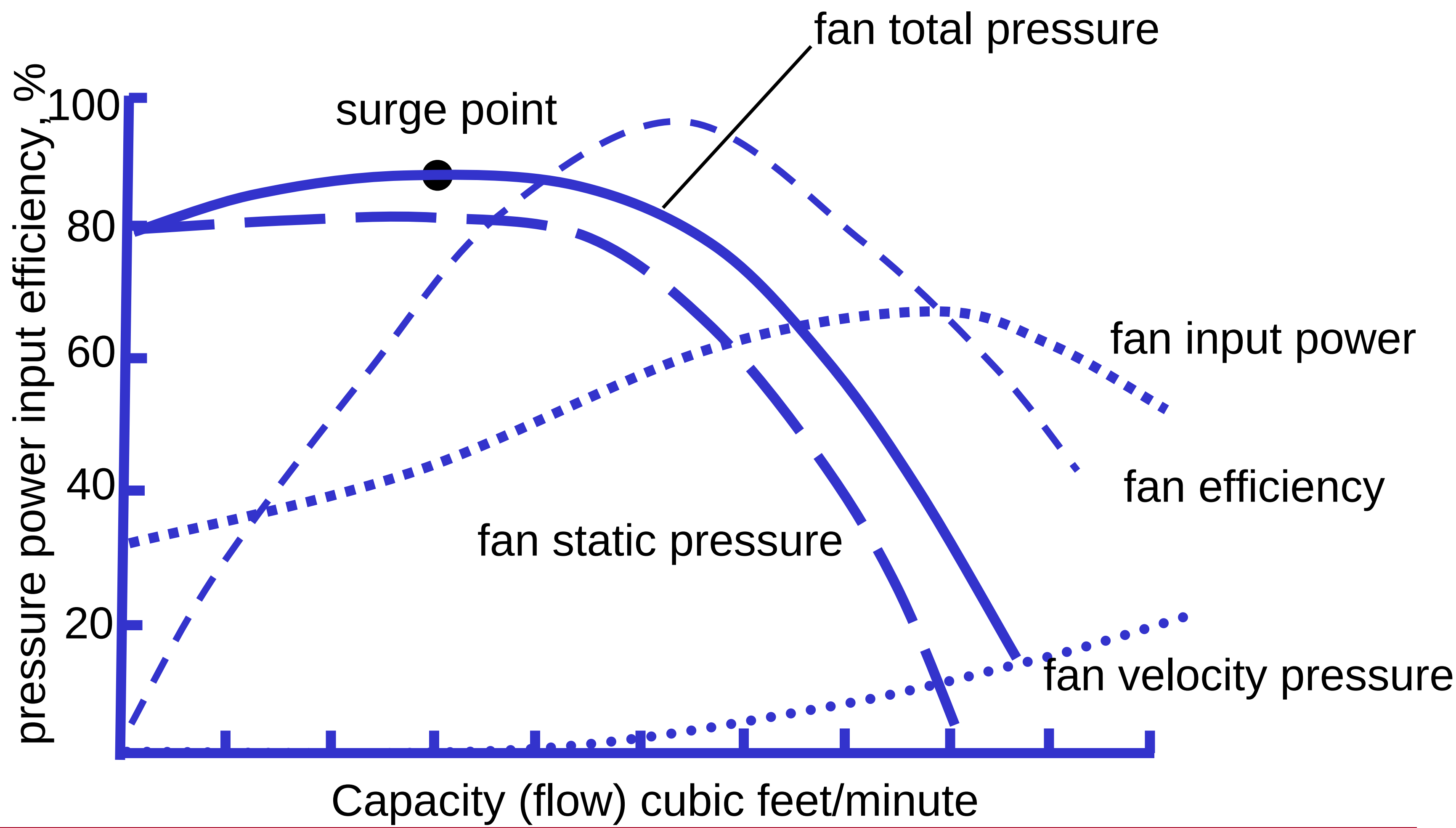
# Fans

Fan efficiency:

- fans - 7% increase in air density
- blowers - higher
- compressors - very high

# Fans

## Fan performance characteristics at constant speed



# Fans

## Principles and characteristics

- Many centrifugal fans have a volute or scroll-type casing, in which the flow enters axially and leaves tangentially
- Blades may be fixed or adjustable
- The best performance is achieved at the intersection of the system characteristics and the fan pressure characteristic both of which can be altered mechanically

# Fans

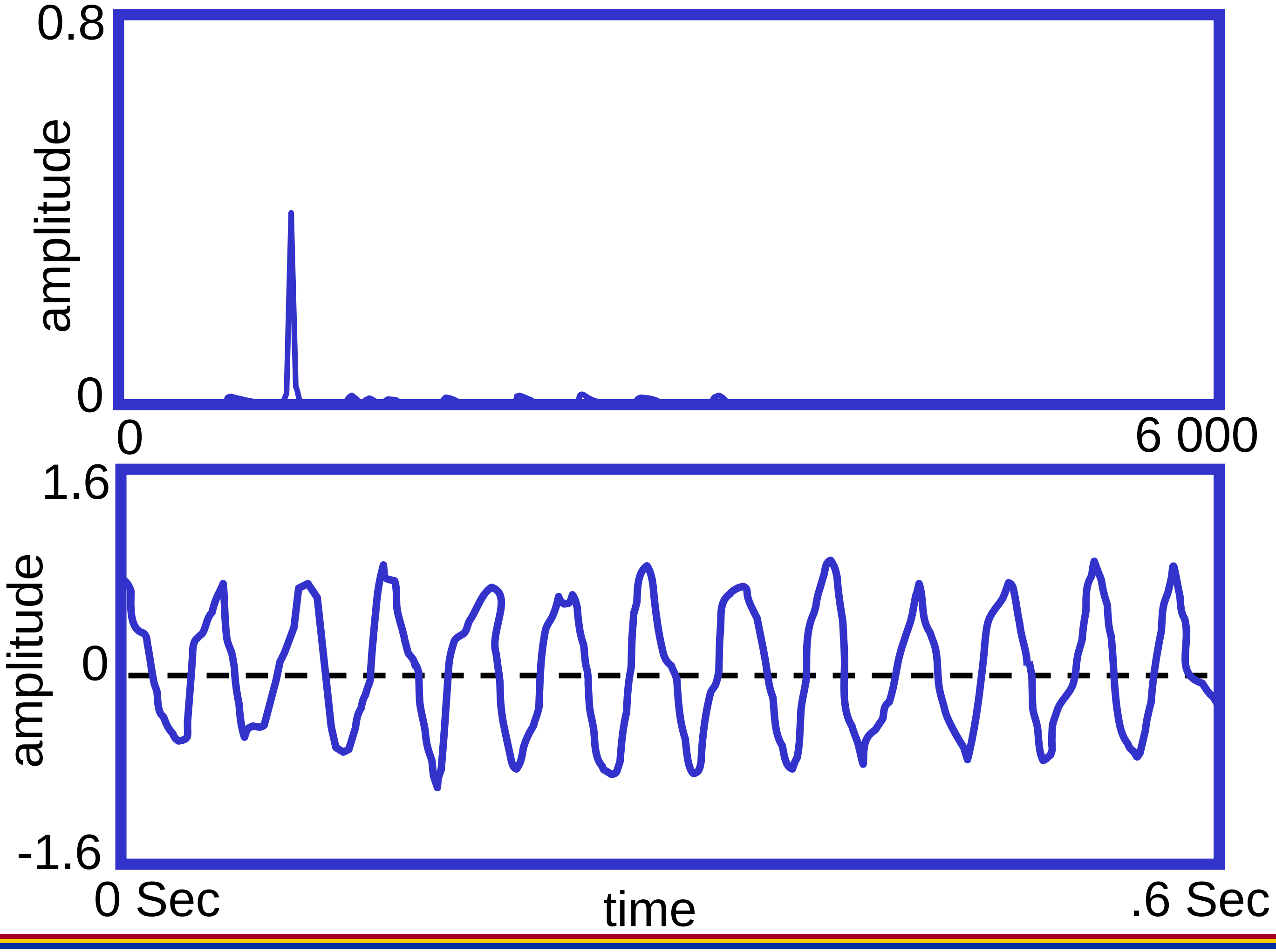
- Most Common Fan Faults:
  - Mass imbalance from build-up (or loss) of material on blades.
  - Misalignment
- Characterised by changes around the rotational frequency
  - Instrumentation:
    - Shaft displacement
    - Or casing vibration

# Vibration Monitoring of Fans

- Mount transducers in plane of least stiffness
- In order to remove the effects of duct noise or other unrelated vibrations:
  - Bandpass filter from 0.5 X Running speed to 3 X running speed

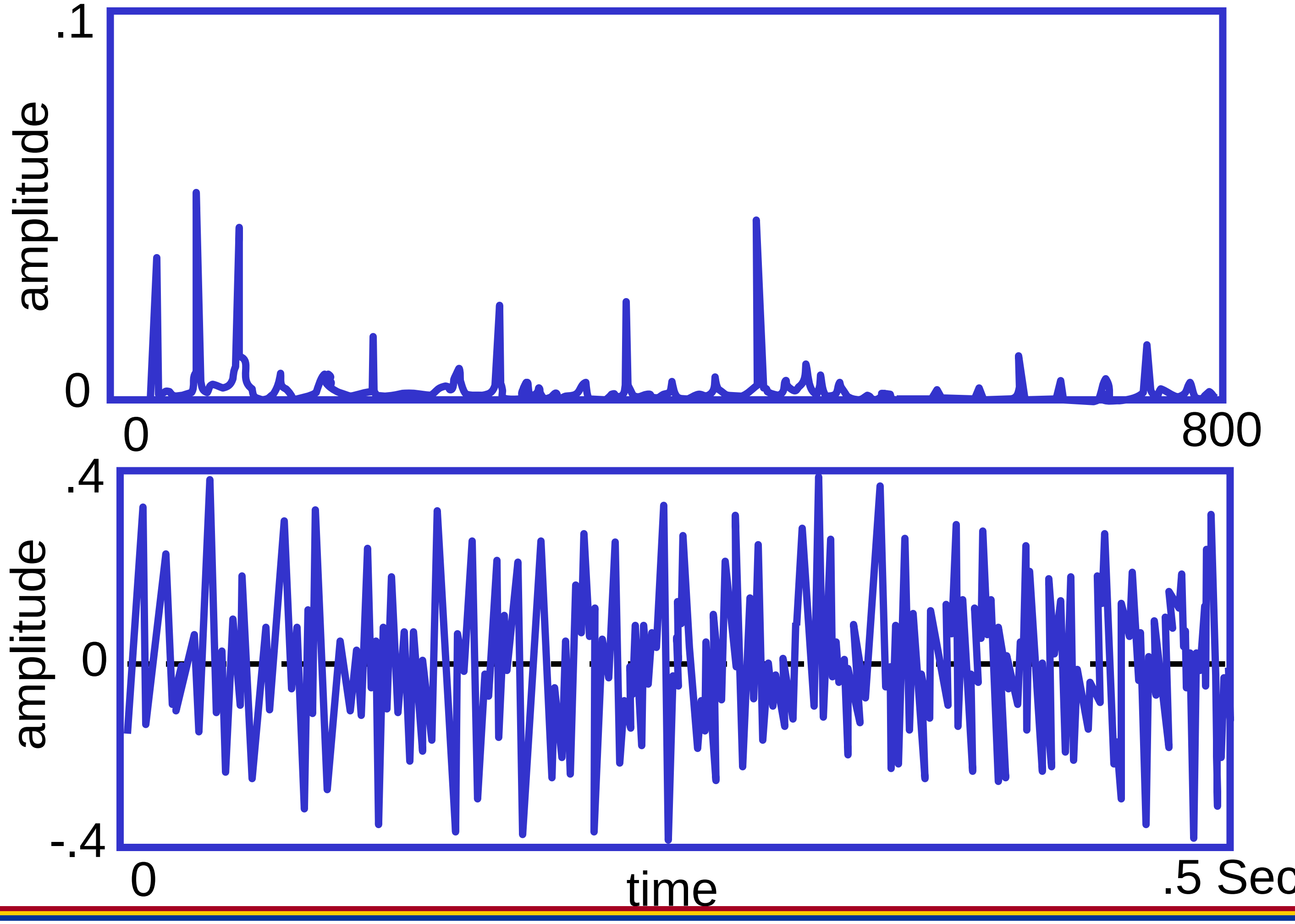
# Fans

- Mass unbalance of a fan



# Fans

- Looseness in a fan bearing



# Fans

## Common fan faults

- Mass unbalance
- Misalignment
- Critical speeds
- Resonance
- Looseness
- Aerodynamic problems
- Isolator problems
- Oil whirl
- Rolling element bearings
- Soft foot
- Impeller eccentricity
- Belts and pulleys

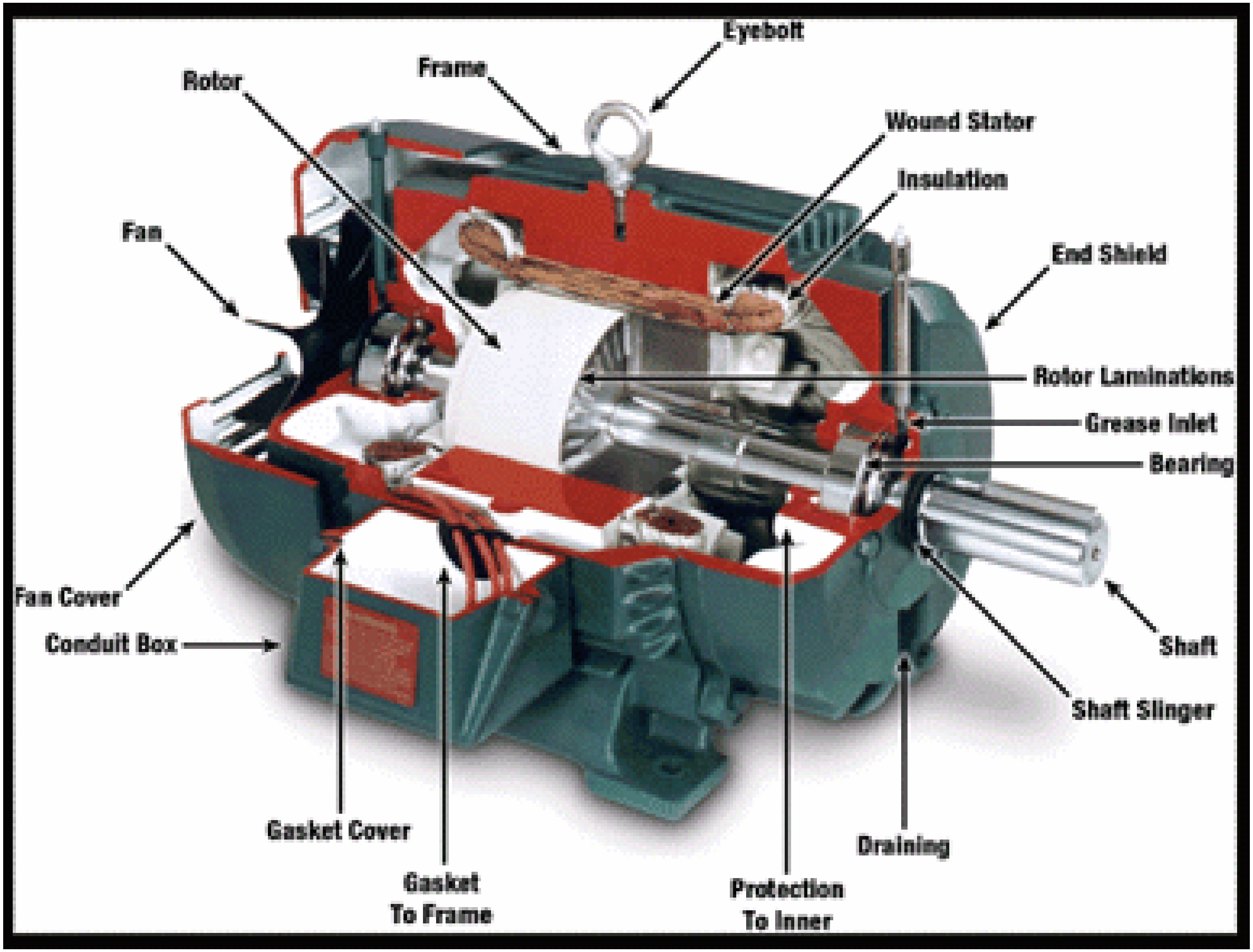
## ELECTRIC MOTORS

- Driven by a voltage at line frequency of 60 Hz (North America)
- The speeds of induction motors are determined by the number of poles
- Synchronous motor speed (SMS)

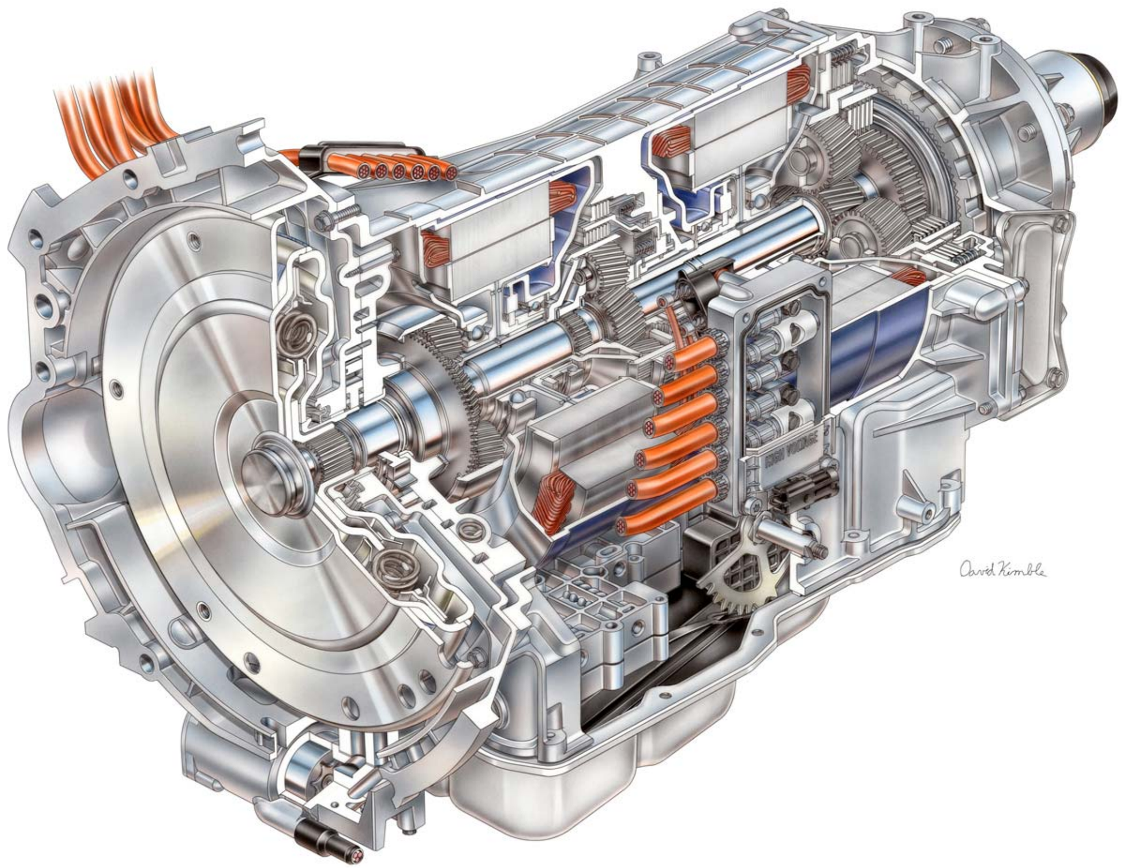
  SMS = 2 x (line frequency)/(number of poles)
- Slip: the difference between SMS and the actual motor speed

# Electric Motors

½ HP



# Electric Motors

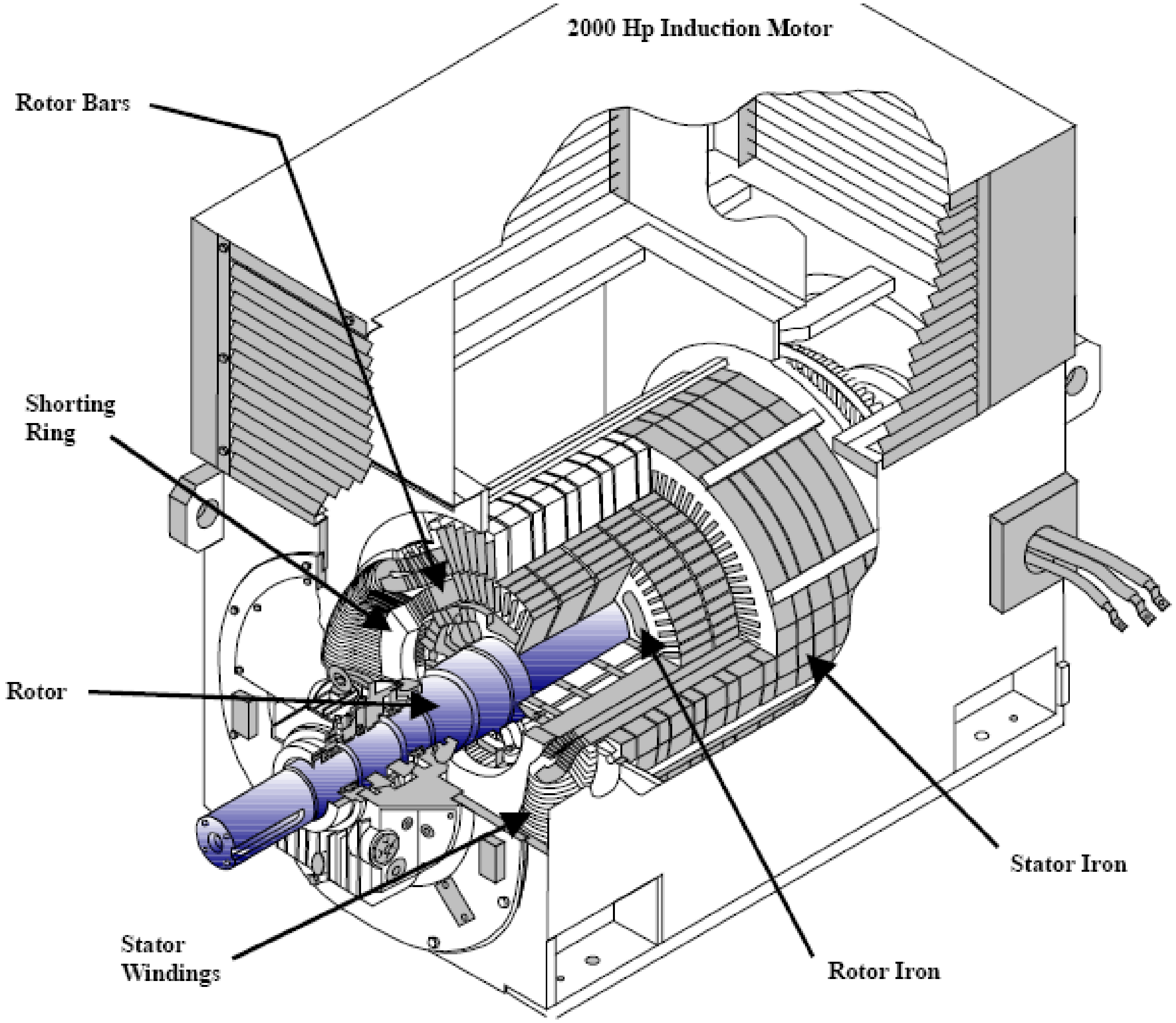


## 2008 GMC Yukon 2-mode Hybrid Transmission/Motor

The transmission unit contains two 60 kW electric motors, three planet gear sets and four hydraulic wet clutches. The combination provides both continuously variable and fixed gear operation as well as electric propulsion all within the same housing

# Electric Motors

## Cut-away diagram of an induction motor



# Electric Motors

## Cut-away diagram of an induction motor

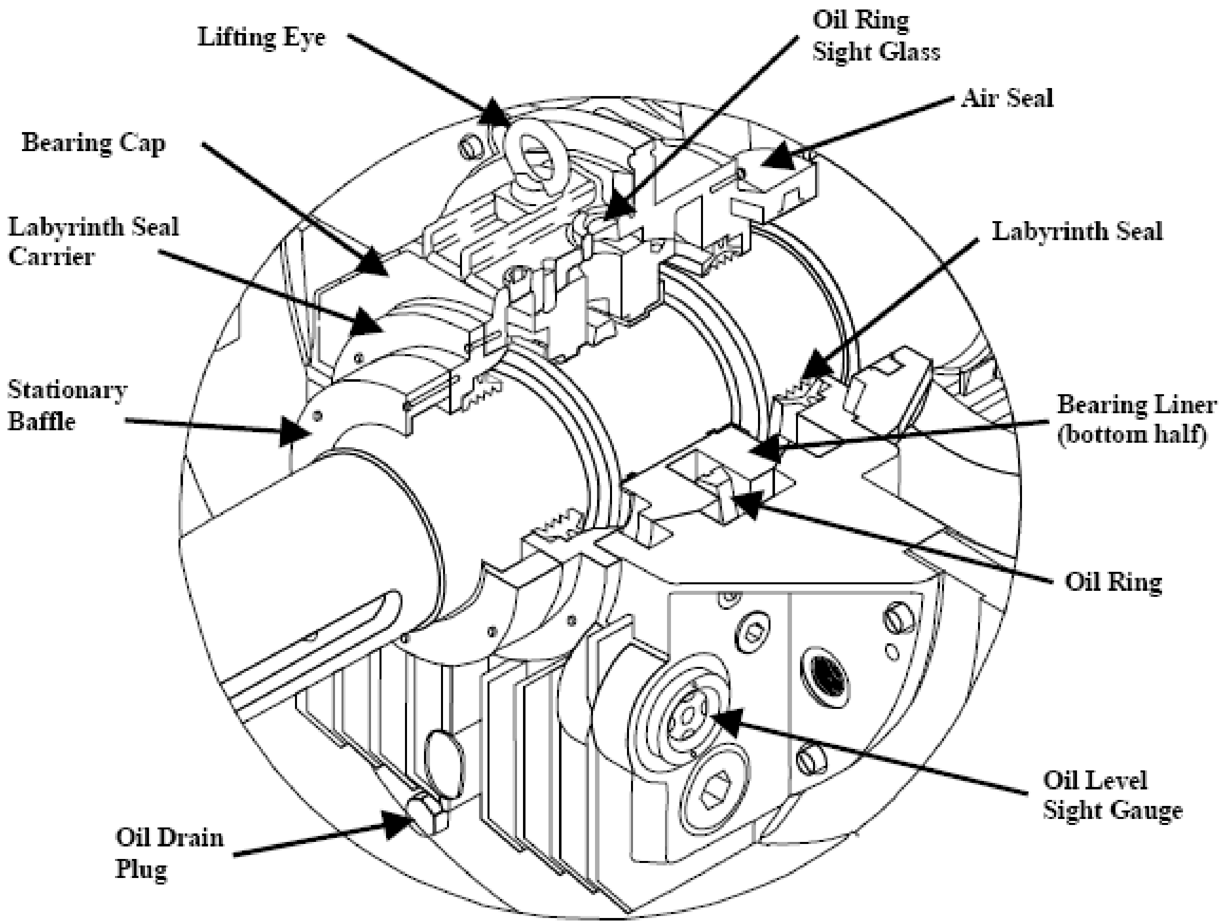
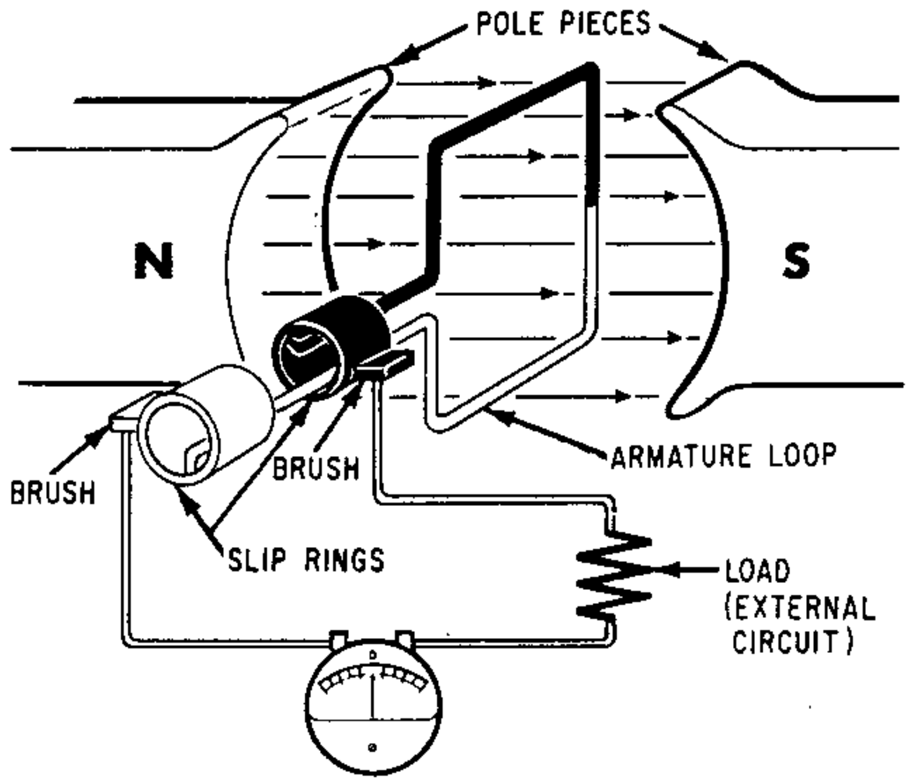


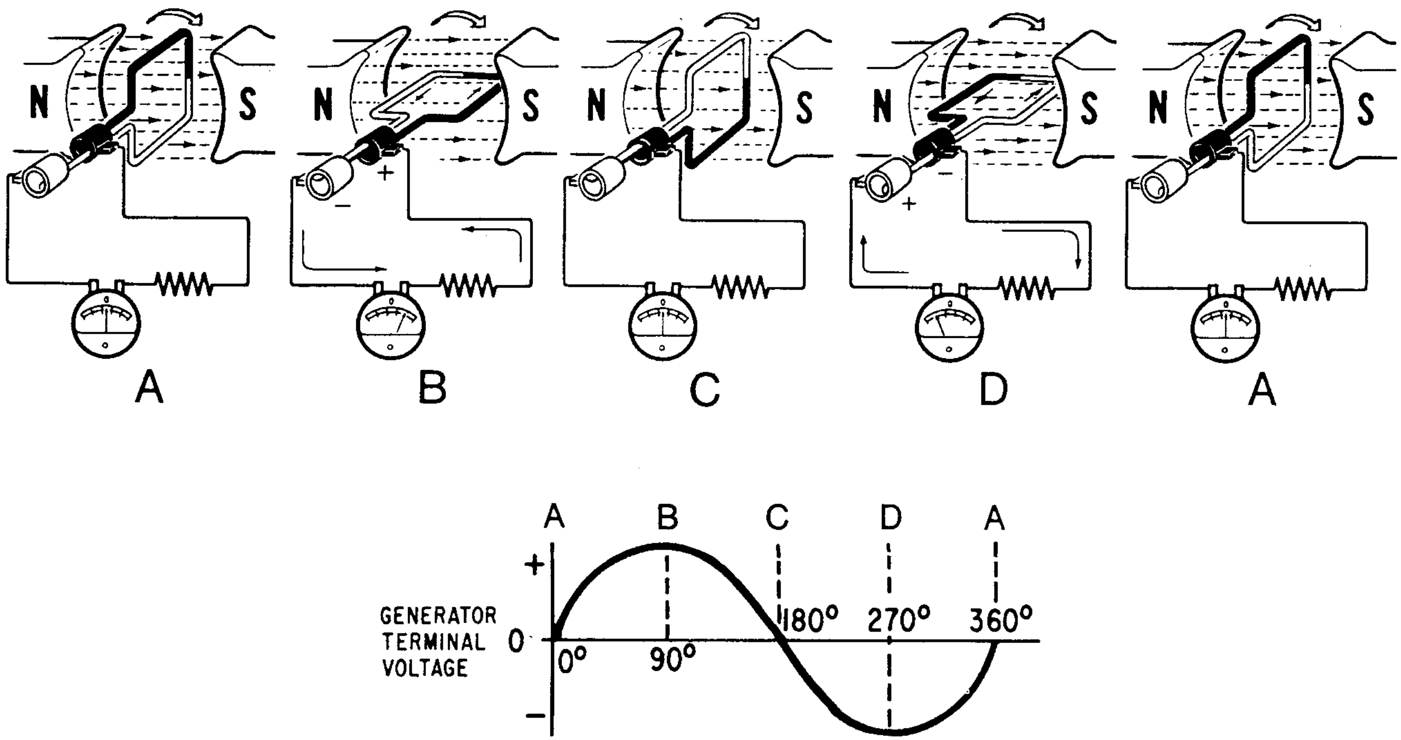

**Figure 2** Electric Motor Endbell Bearing Assembly

# Electric Motors

To generate electricity move a coil of wire across magnetic lines of flux

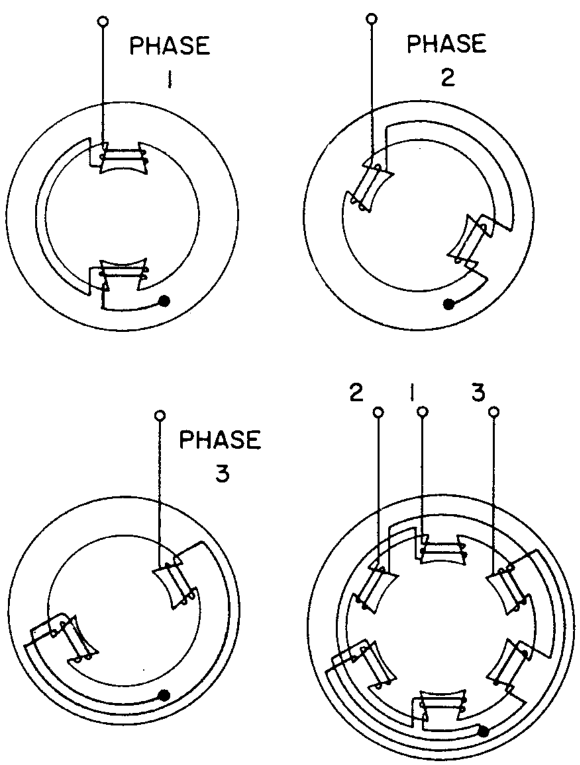


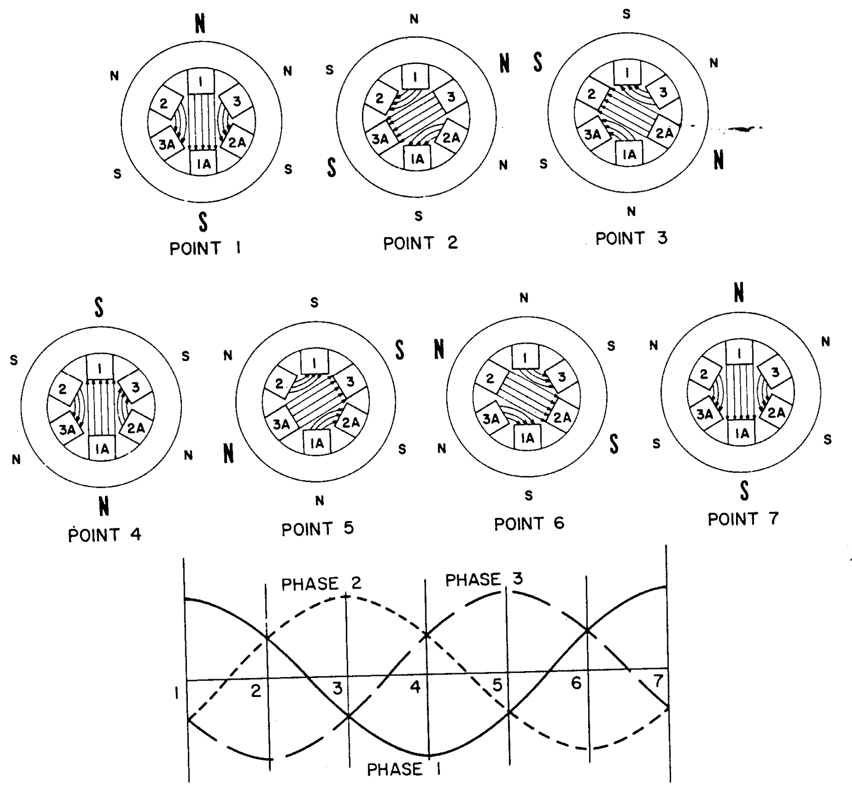
# Electric Motors



# Electric Motors

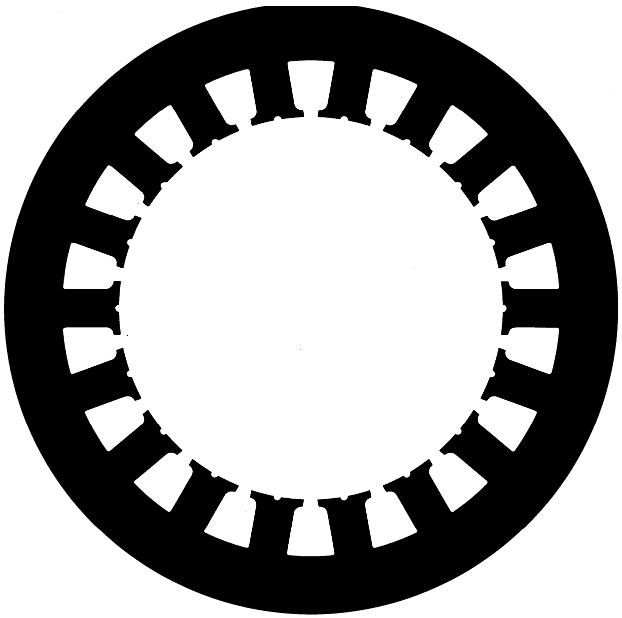
To use electricity to move a coil of wire you must first create a moving magnetic field



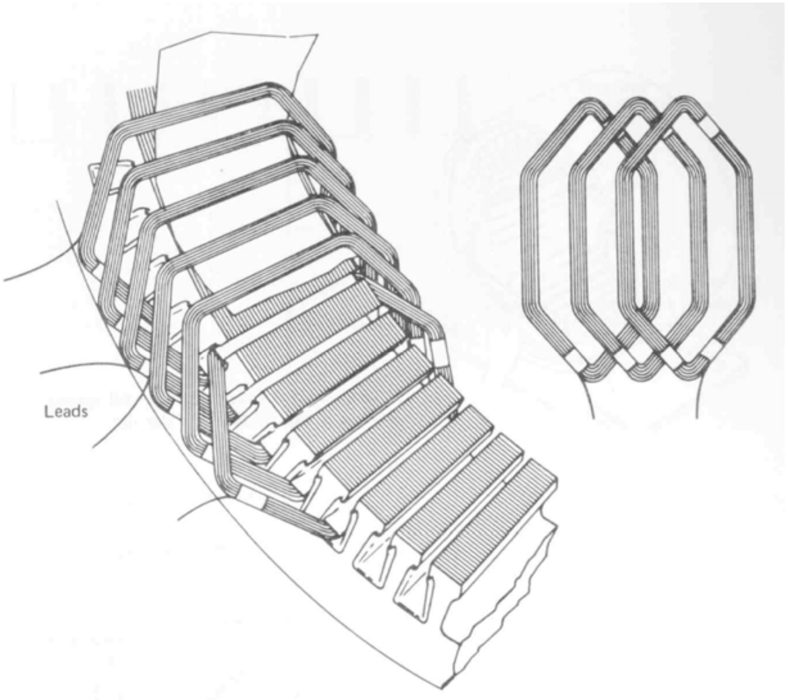



# Electric Motors

Stator – holds windings that create the moving magnetic field



Stator windings – insulated copper wire rapped in coils

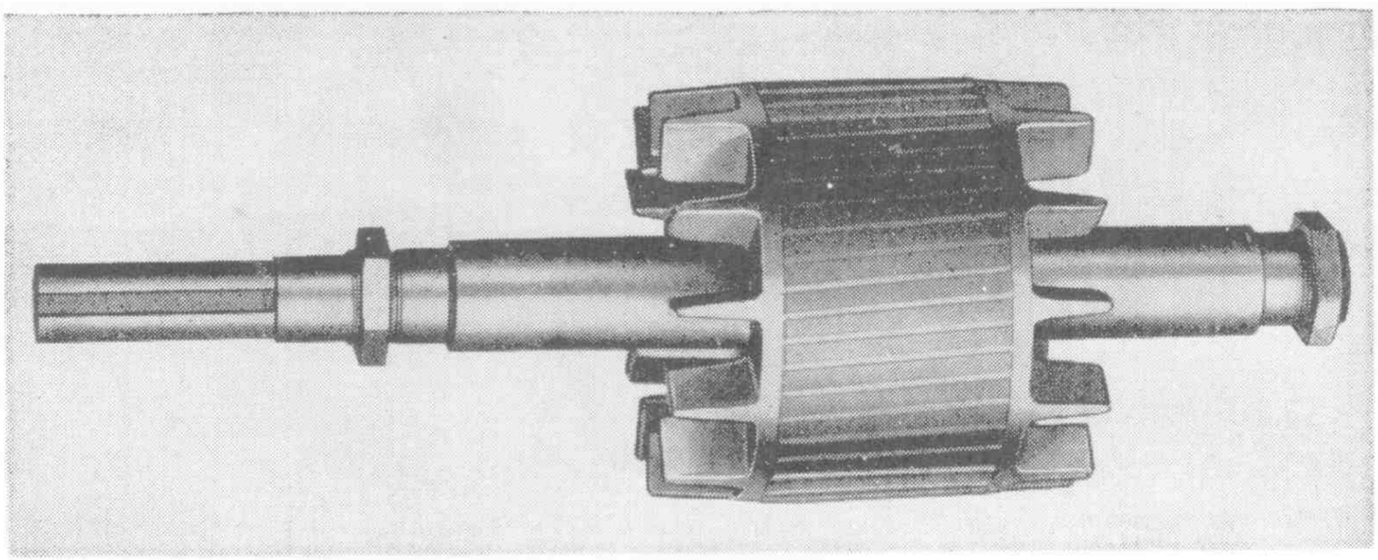


# Electric Motors

Magnetic material used for the stator core is by nature also a conductor. Voltage induced in the core steel causes a current to flow in the core. This eddy current flow in the core raises stator temperature and lowers motor efficiency. A laminated core offers high resistance to current flow; hence, the eddy currents and resulting losses are reduced.

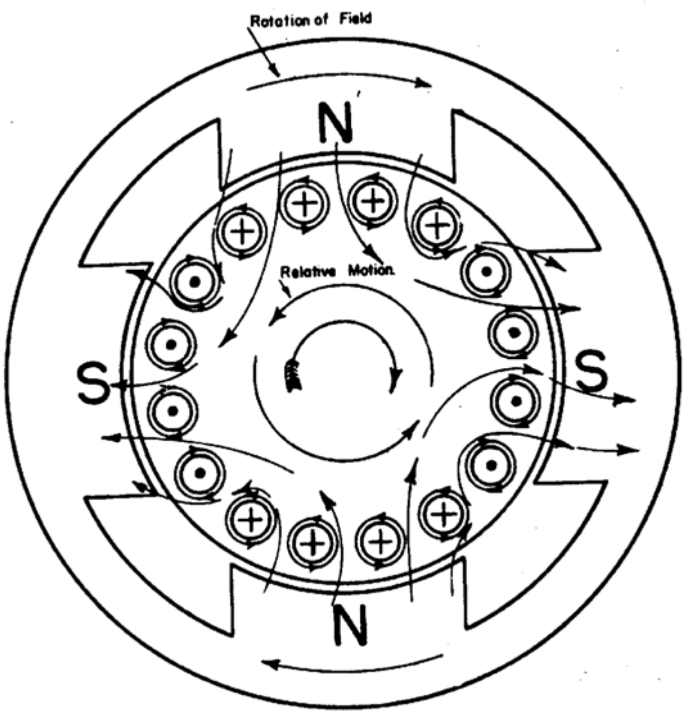
# Electric Motors

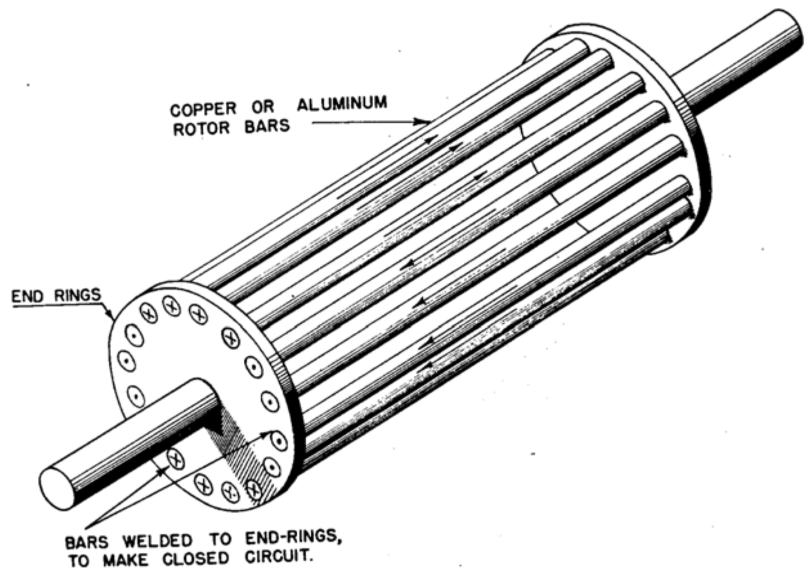
The rotor – rotational element of the electric motor. A squirrel cage rotor design is commonly used in most induction motors. This design uses a laminated slotted core in which the conductive material for the rotor bars is placed in the slots. The rotor bars are then shorted together by the end rings.



# Electric Motors

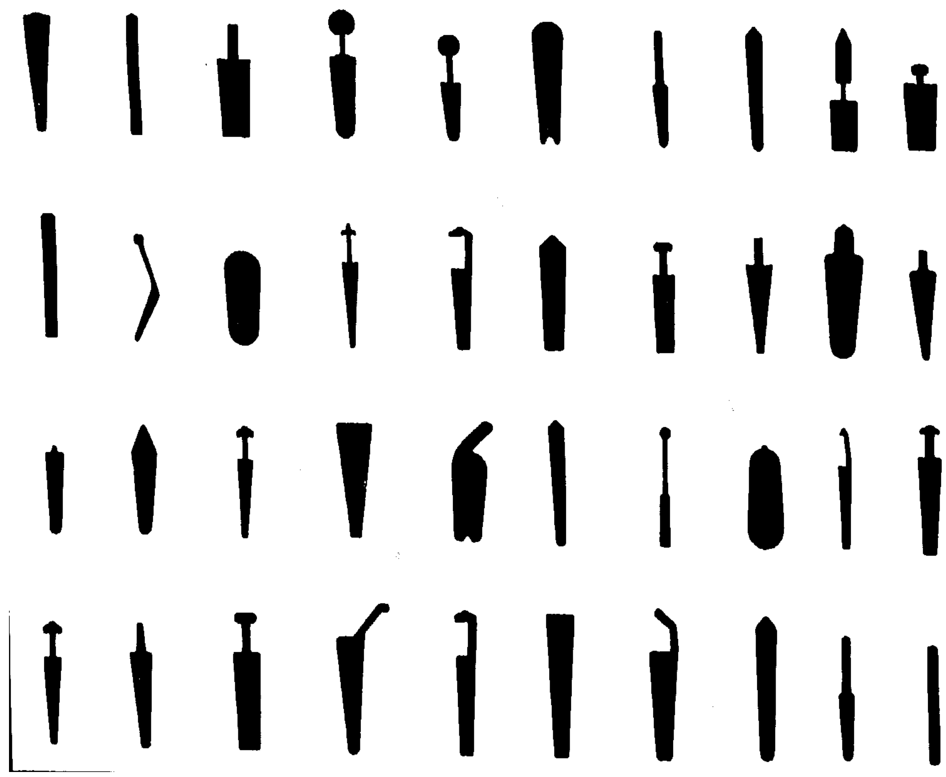
Squirrel cage induction motors have very few maintenance requirements, and they have a rugged and dependable reputation. You can double-wind the squirrel cage with a high and low resistance winding. This configuration combines both high starting torque and excellent constant speed control



# Electric Motors

## Rotor Bar Shapes



## Electric motor malfunctions – mechanical effects

- Mass unbalance
- Looseness
- Resonance
- Misalignment
- Eccentricity
- Bearing defects
- Distortion

## Electric motor malfunctions – electrical effects

| Fault | Frequency | Spectrum; Time Waveform/Orbit Shape | Correction/Comment |
|---|---|---|---|
| air-gap variation | 120 Hz | 120 Hz plus sidebands, beating 2x with 120 Hz | center armature relieving distortion on frame; eliminating excessive bearing clearance and/or any other condition that causes rotor to be off center with stator |
| broken rotor bars | 1x | 1x and sidebands equal to (number of poles x slip frequency) | replace loose or broken rotor bars |
| eccentric rotor | 1x | 1x, 2x/120-Hz beats possible | may cause air-gap variation |
| stator flexibility | 120 Hz | 2x/120-Hz beats | stiffen stator structure |
| off magnetic center | 1x, 2x, 3x | impacting in axial direction | remove source of axial constraint-bearing thrust, coupling |
| stator shorts | 120 Hz and harmonics | 120 Hz and harmonics | replace stator |

# Electric Motors

## Electric motor malfunctions

### *Stator Eccentricity, Shorted Laminations and Loose Iron*

- Stator problems generate high vibration at 2X line frequency (2FL).
- Stator eccentricity produces uneven stationary air gap between the rotor and the stator which produces very directional vibration
- Differential air gap should not exceed 5% for induction motors and 10% for synchronous motors
- Soft foot and warped bases can produce an eccentric stator
- Loose iron is due to stator support weakness or looseness
- Shorted stator laminations cause uneven, localized heating which can significantly grow with operating time.

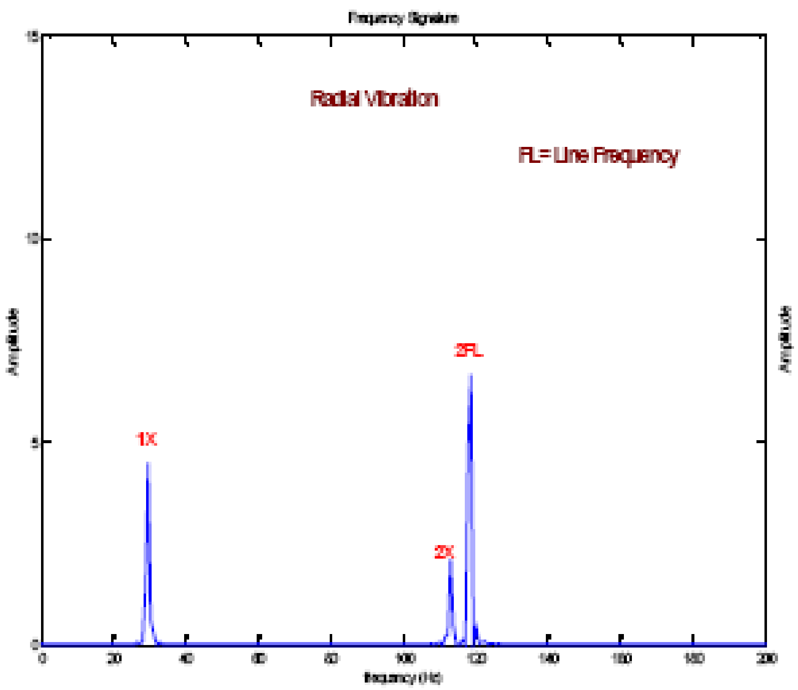
# Electric Motors

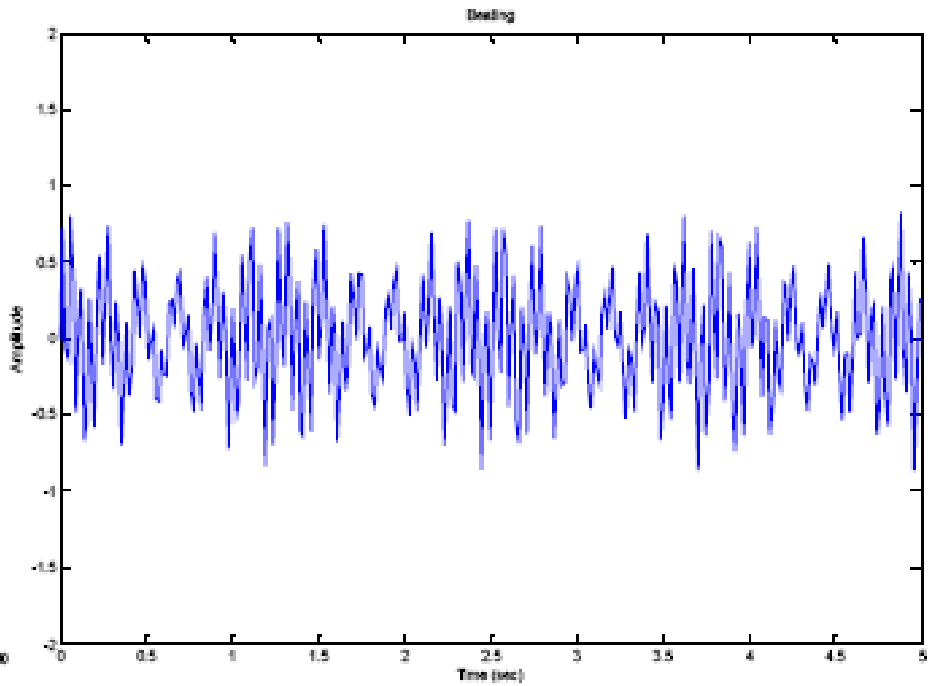
## Electric motor malfunctions

### *Eccentric Air Gap (Variable air gap)*

- Eccentric Rotors produce a rotating variable air gap between rotor and stator which induces pulsating vibration (normally between (2FL) and closest running speed harmonic).
- Often requires "zoom" spectrum to separate the (2FL) and the running speed harmonic
- Eccentric rotors generate (2FL) surrounded by Pole Pass frequency sidebands (FP) as well as FP sidebands around running speed FP appears itself at low frequency (Pole Pass Frequency = Slip Frequency x # Poles)
- Slip Frequency , $F_s = N_s - RPM$
- Synchronous speed , $N_s = 120\ F_L/P$
- $P$ , # of Poles
- Common values of FP range from approximately 20 to 120 CPM (.30 - 2.0 Hz)

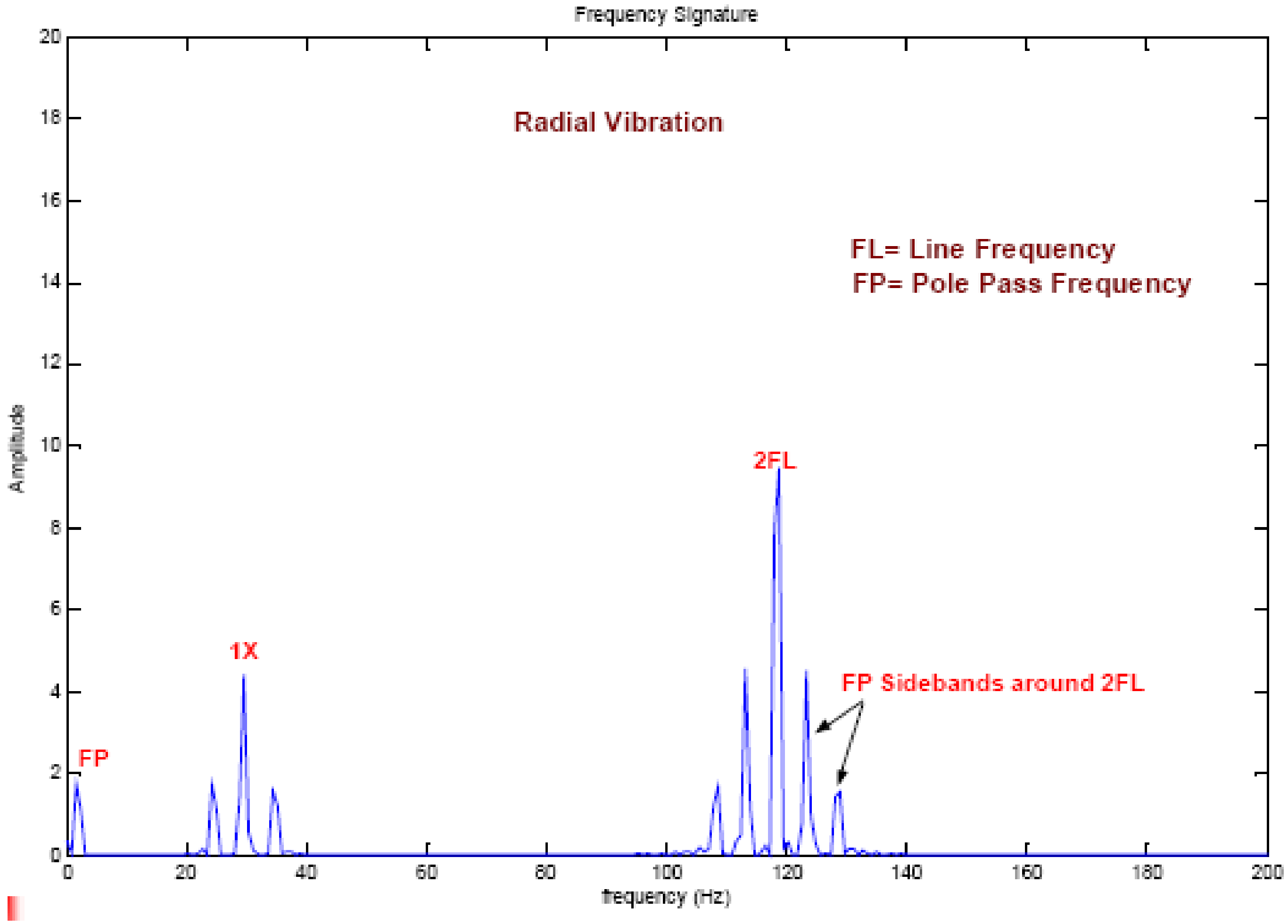
## Eccentric Rotor (Variable Air Gap)



# Electric Motors

## Eccentric Rotor (variable air gap)



# Electric Motors

## *Rotor Problems*

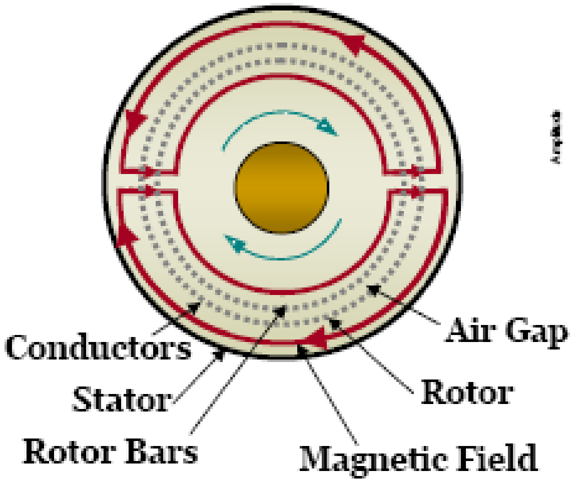
- Broken or Cracked rotor bars or shorting rings, bad joints between rotor bars and shorting rings, or shorted rotor laminations will produce high 1x running speed vibration with pole pass frequency sidebands (**FP**)

- In addition, cracked rotor bars will often generate **FP** sidebands around the 3rd, 4th and 5th running speed harmonics

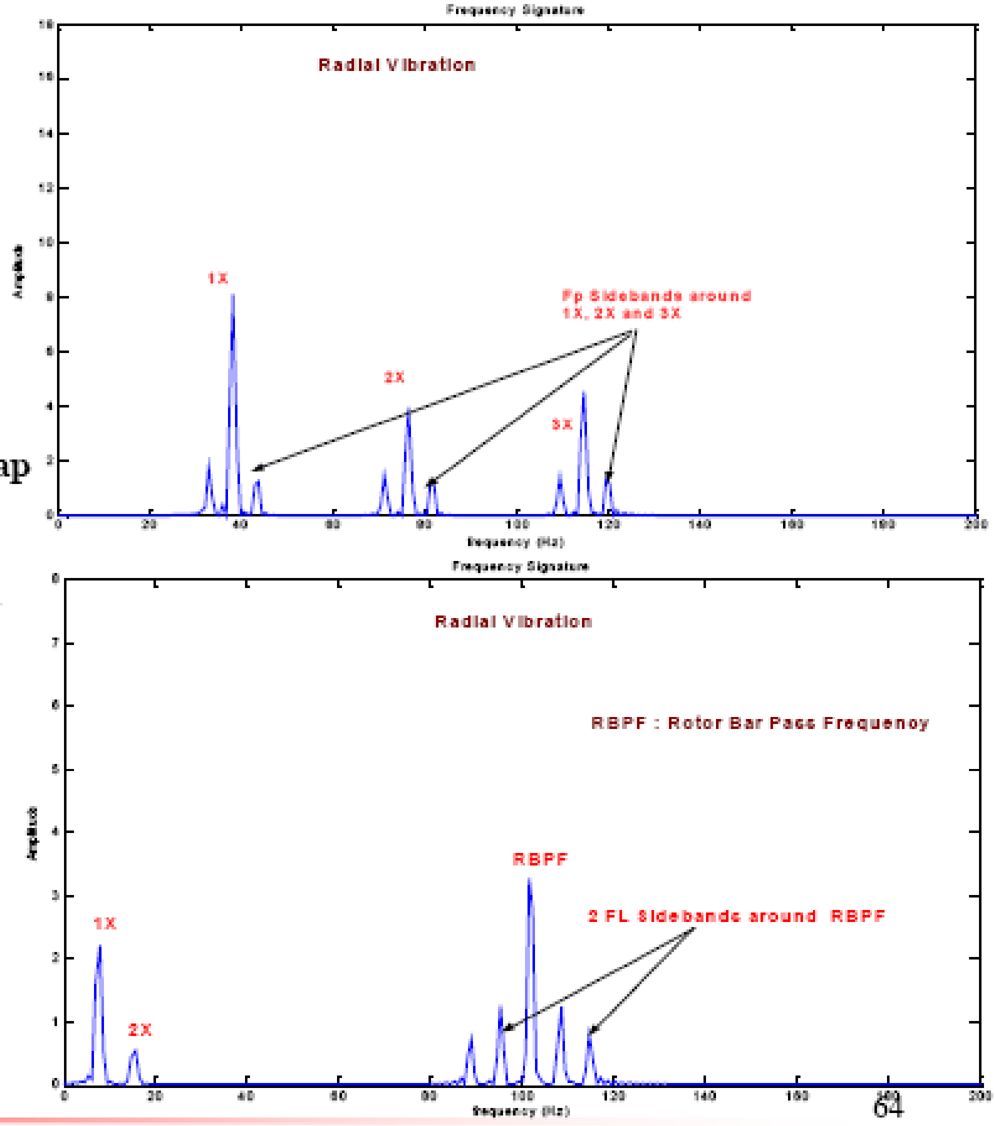
- Loose rotor bars are indicated by 2X line frequency (2FL) sidebands surrounding the rotor bar pass frequency (**RBPF**) and/or its harmonics
(RBPF = Number of rotor bars x RPM)

- Often will cause high levels at 2X RBPF with only small amplitude at 1X **RBPF**.

# Electric Motors




Broken or Cracked Rotor Bars



# Electric Motors

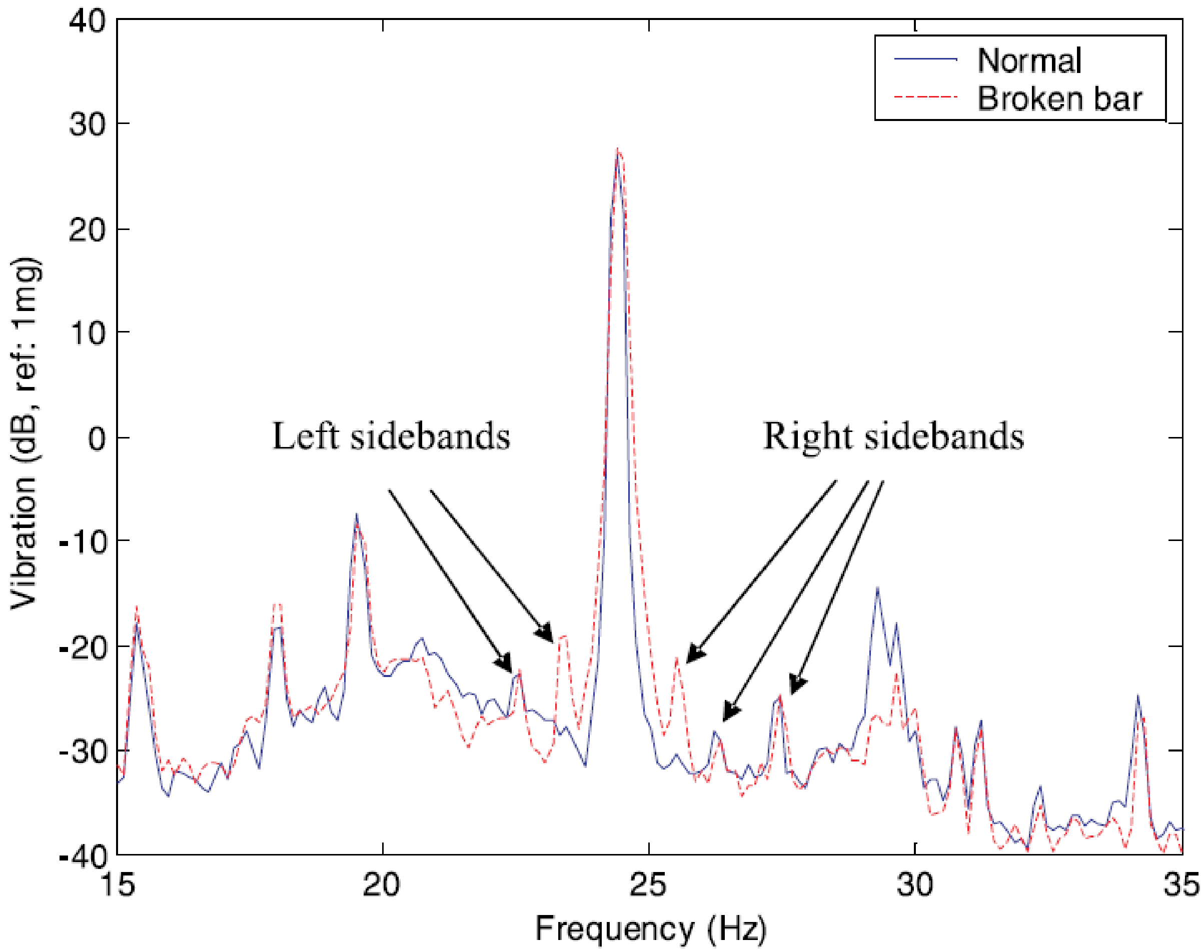



Figure 2. Radial vibration spectra of normal and faulty motors.

# Electric Motors

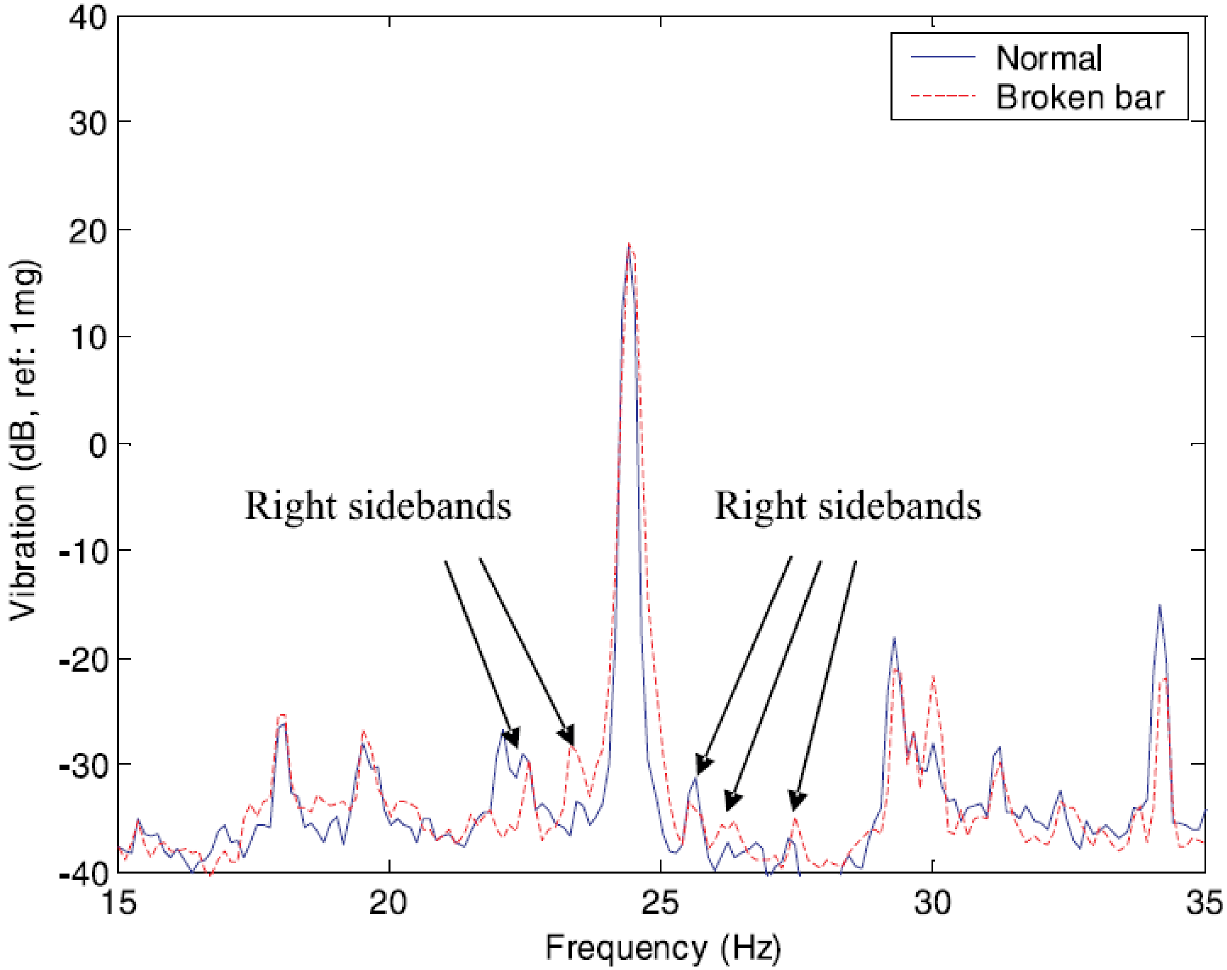
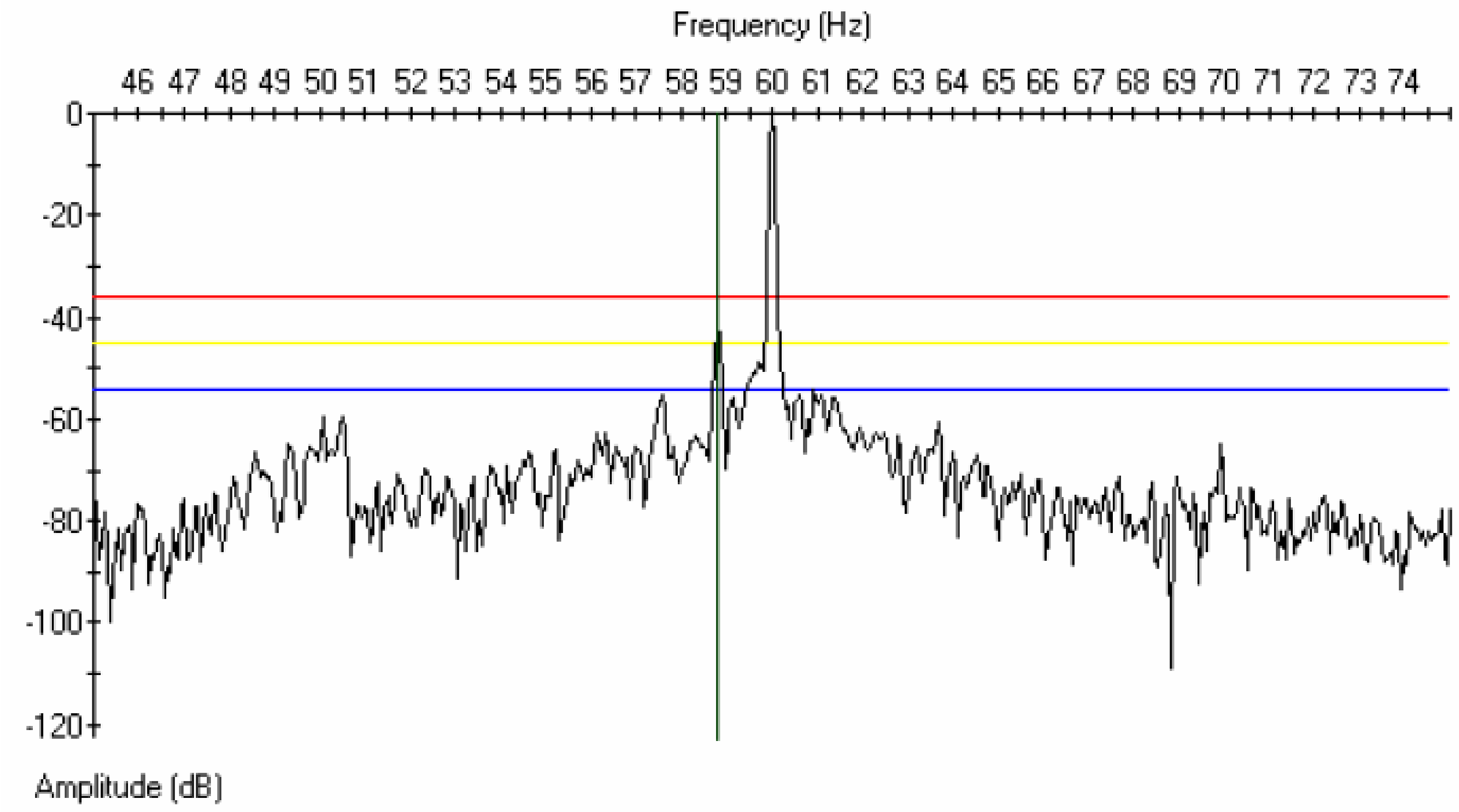



Figure 3. Axial vibration spectra of normal and faulty motors.

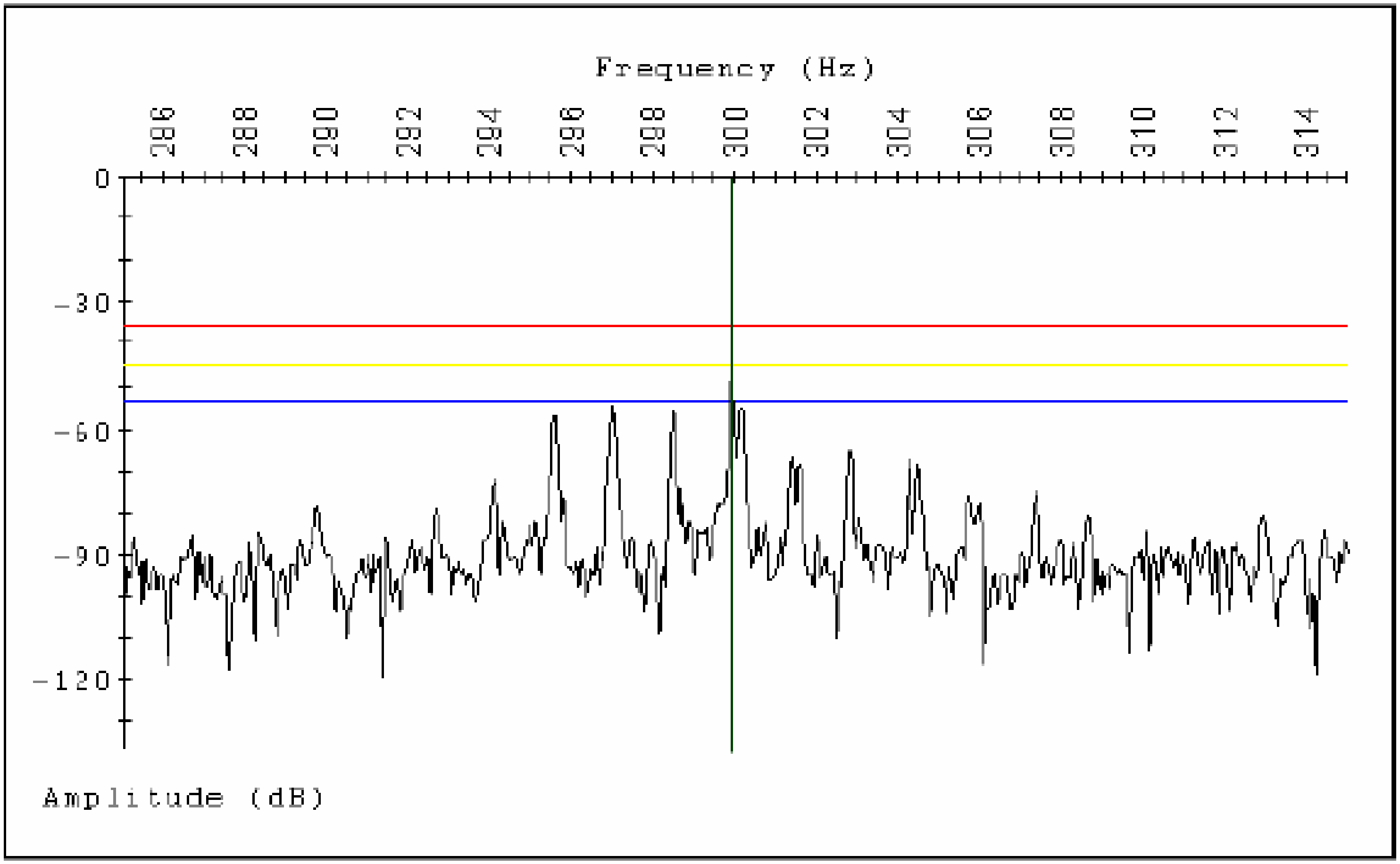
# Suspected Rotor Bar Problem #1




First Indication of a bad rotor bar.

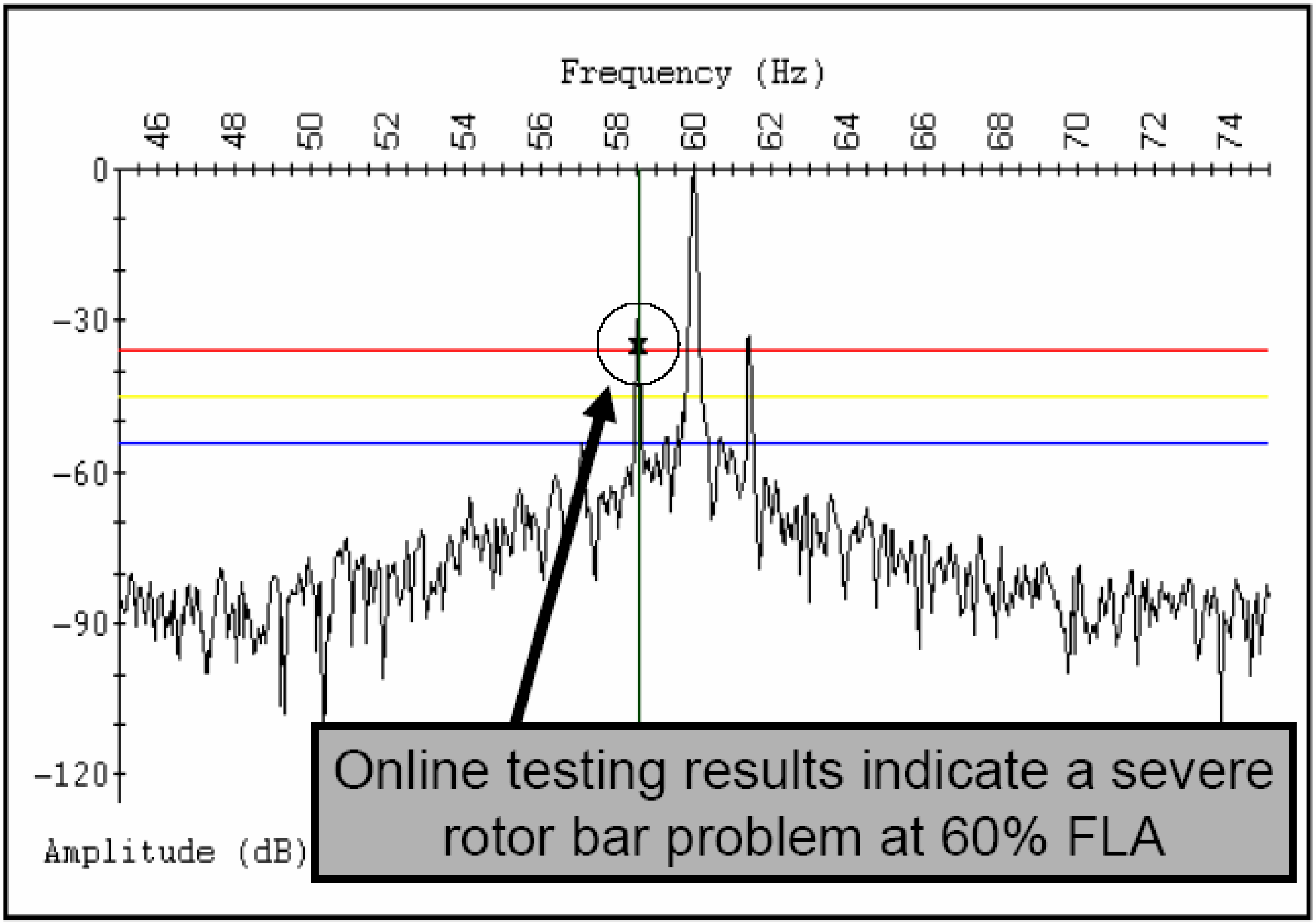
# Suspected Rotor Bar Problem #1

# Suspected Rotor Bar Problem #1

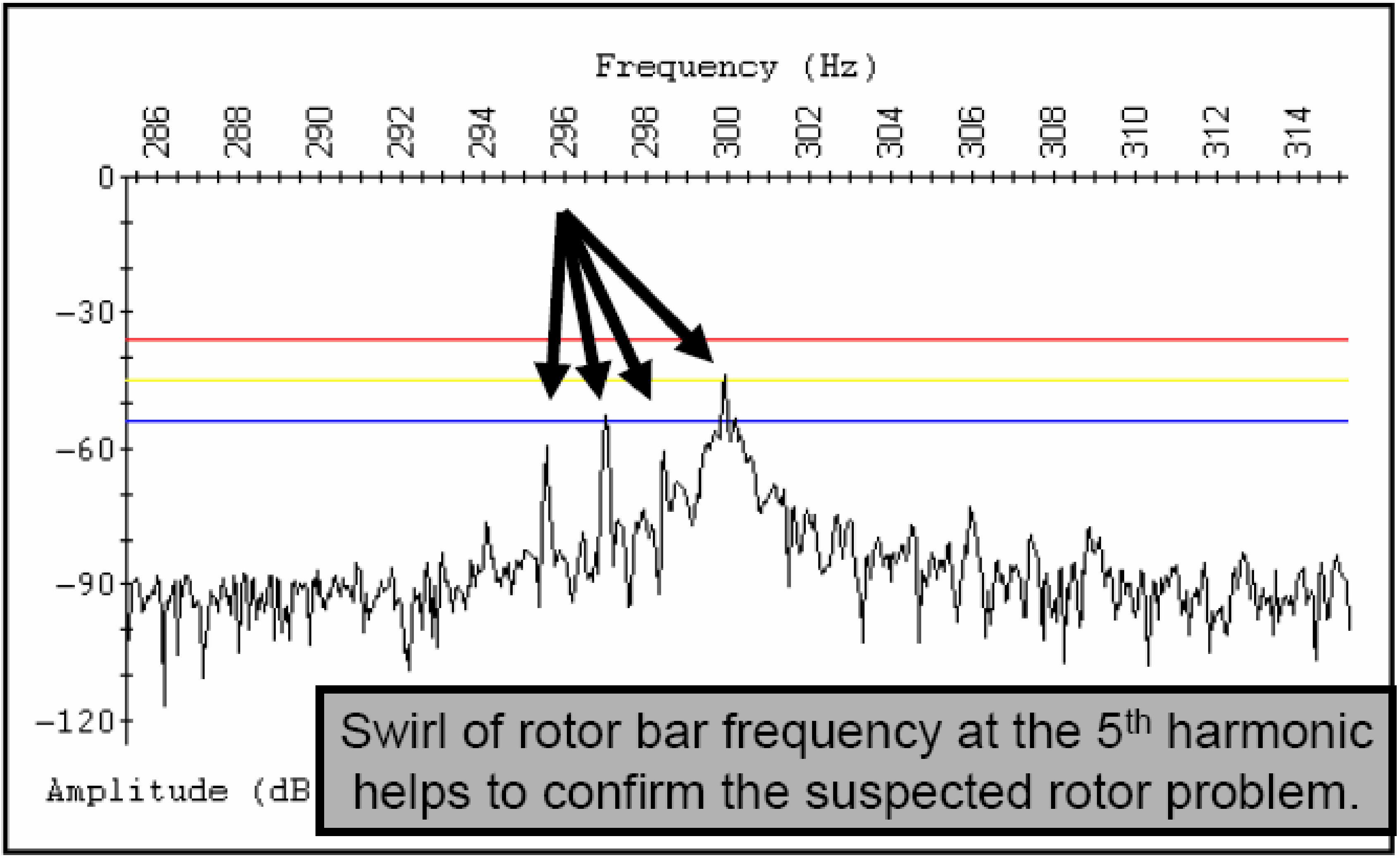



Verification of rotor bar problem – swirl or multiples of pole pass frequencies around 300 Hz or 5 times line frequency.

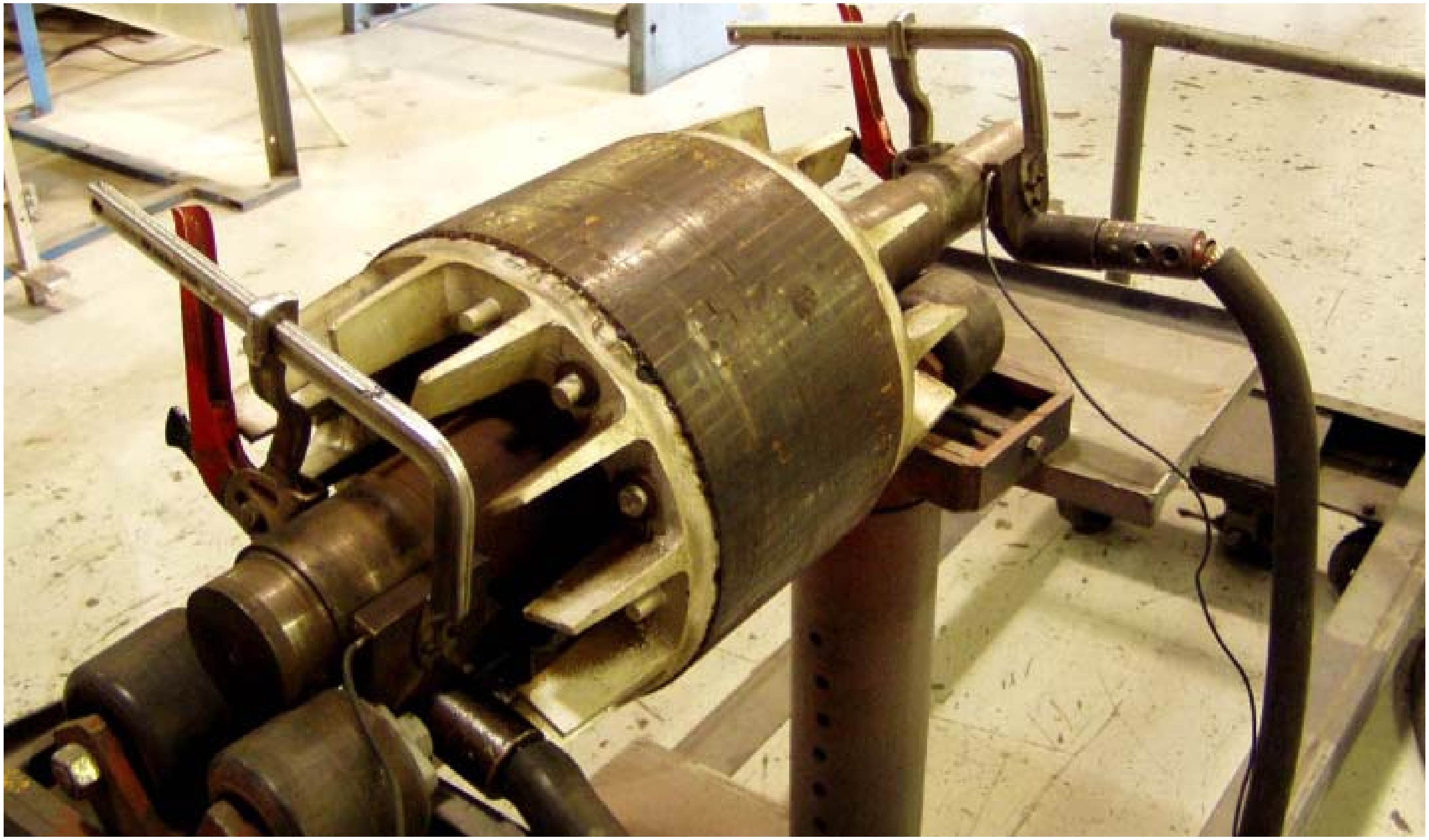
# Suspected Rotor Bar Problem #2



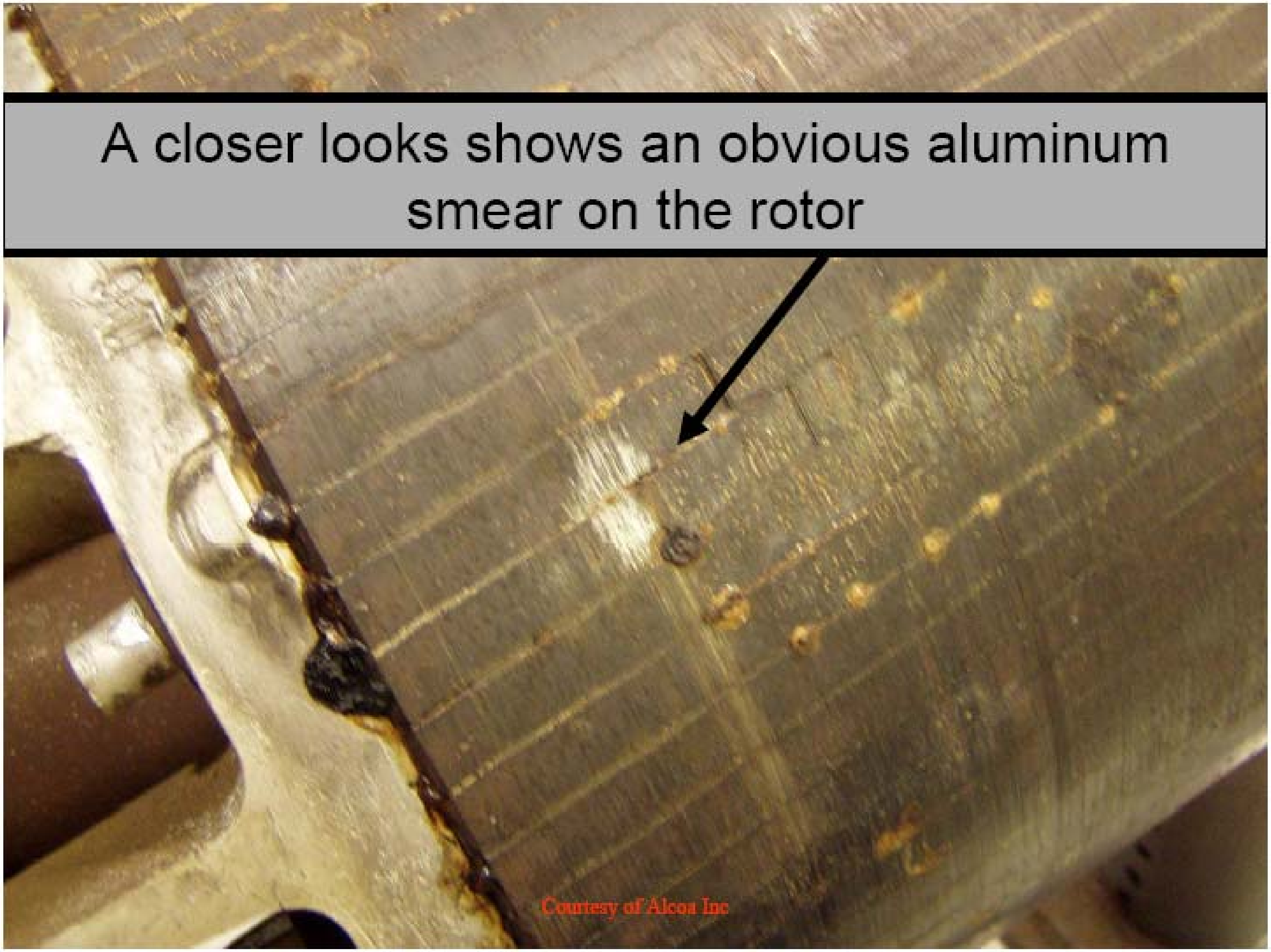
# Suspected Rotor Bar Problem #2



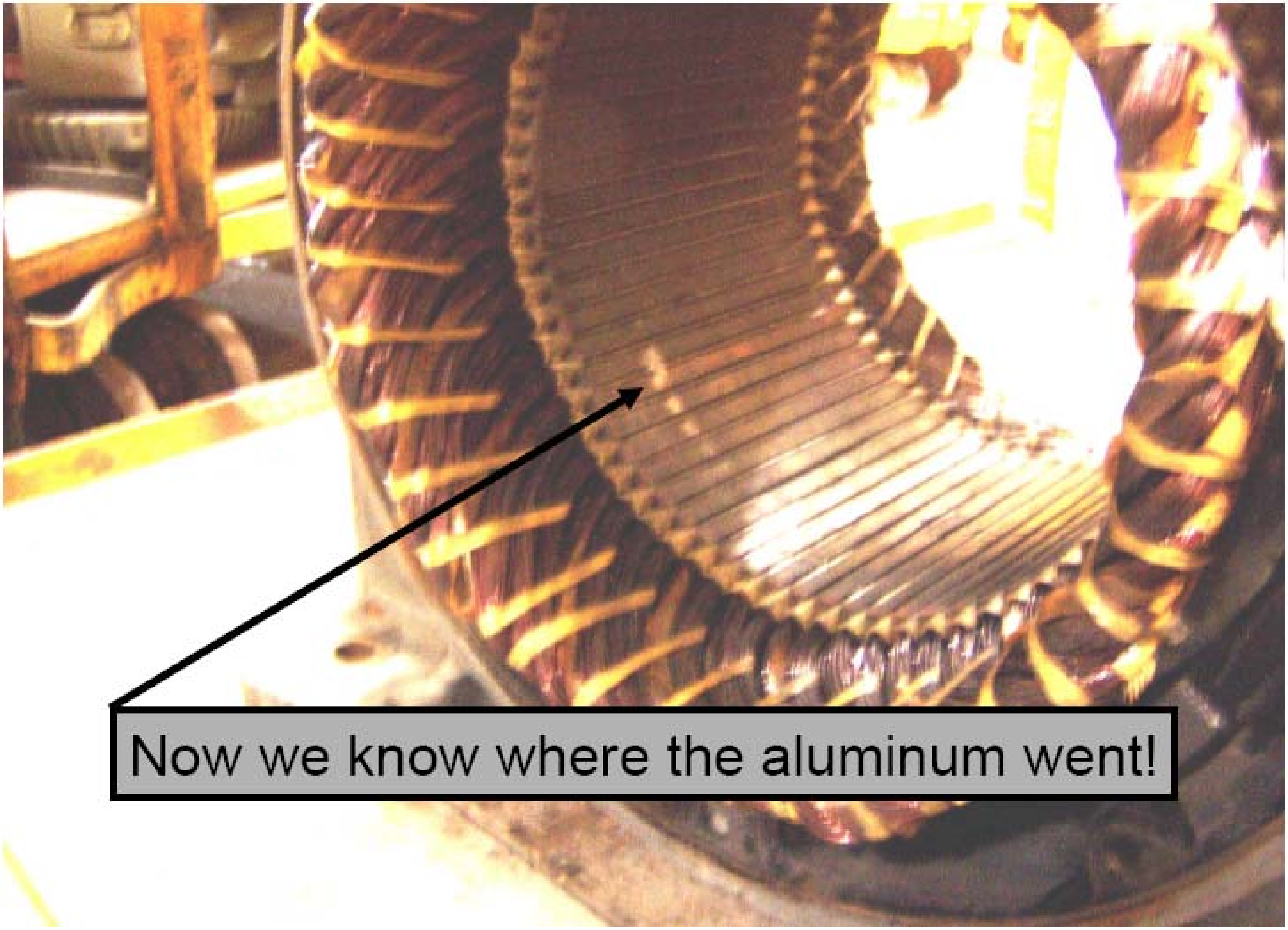
# Suspected Rotor Bar Problem #2



# Suspected Rotor Bar Problem #2



# Suspected Rotor Bar Problem #2



# Electric Motors

*Phasing Problem ( Loose Connector )*

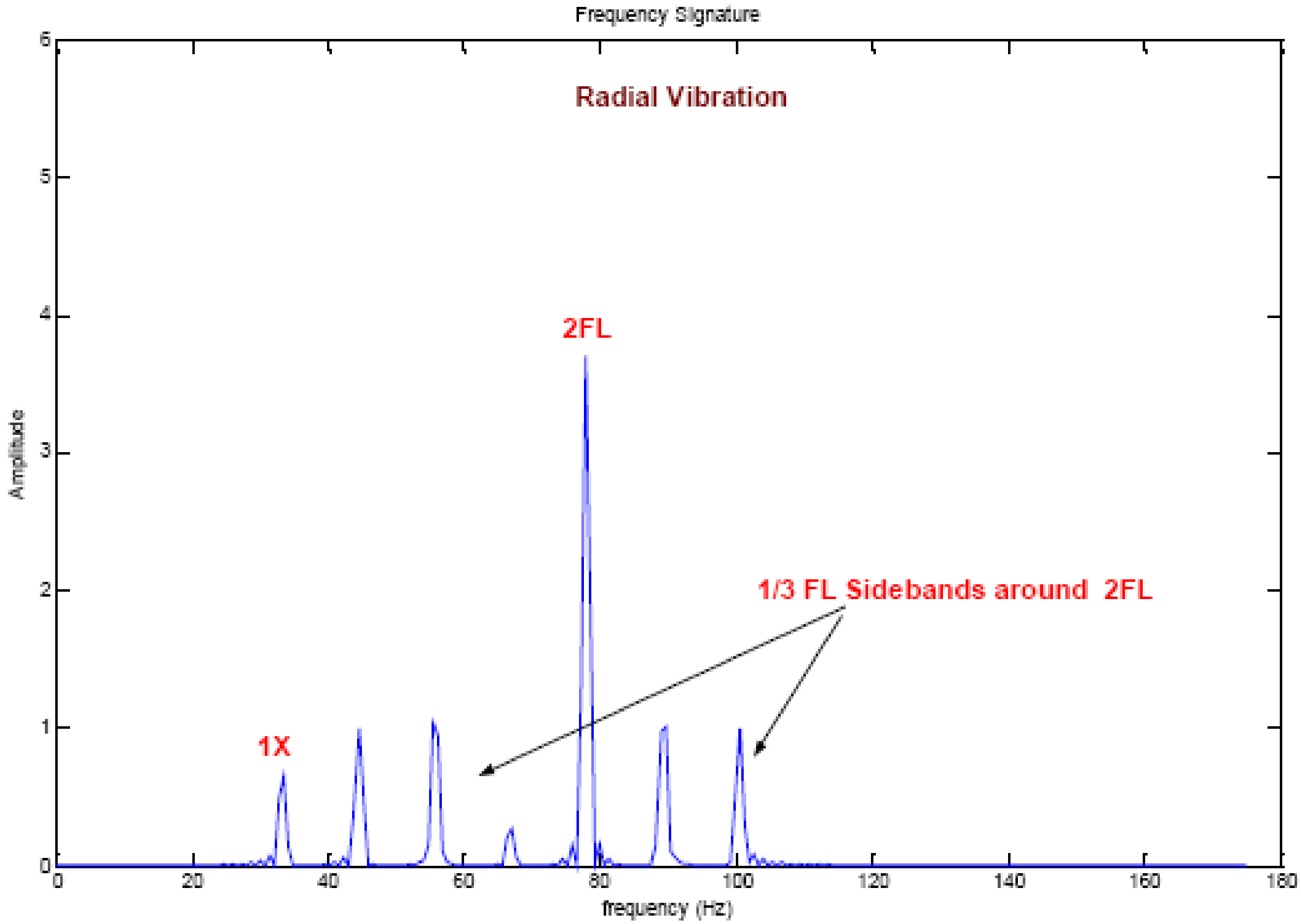
- Phasing problems due to loose or broken connectors can cause excessive vibration at 2X Line frequency (2FL) which will have sidebands around it at 1/3 rd Line Frequency (1/3 FL)

- Levels at (2FL) can exceed 25 mm/s (1.0 in/s) if left uncorrected

- This is particularly a problem if the defective connector is only sporadically making contact and periodically not

# Electric Motors

## Phasing Problems (loose connections)



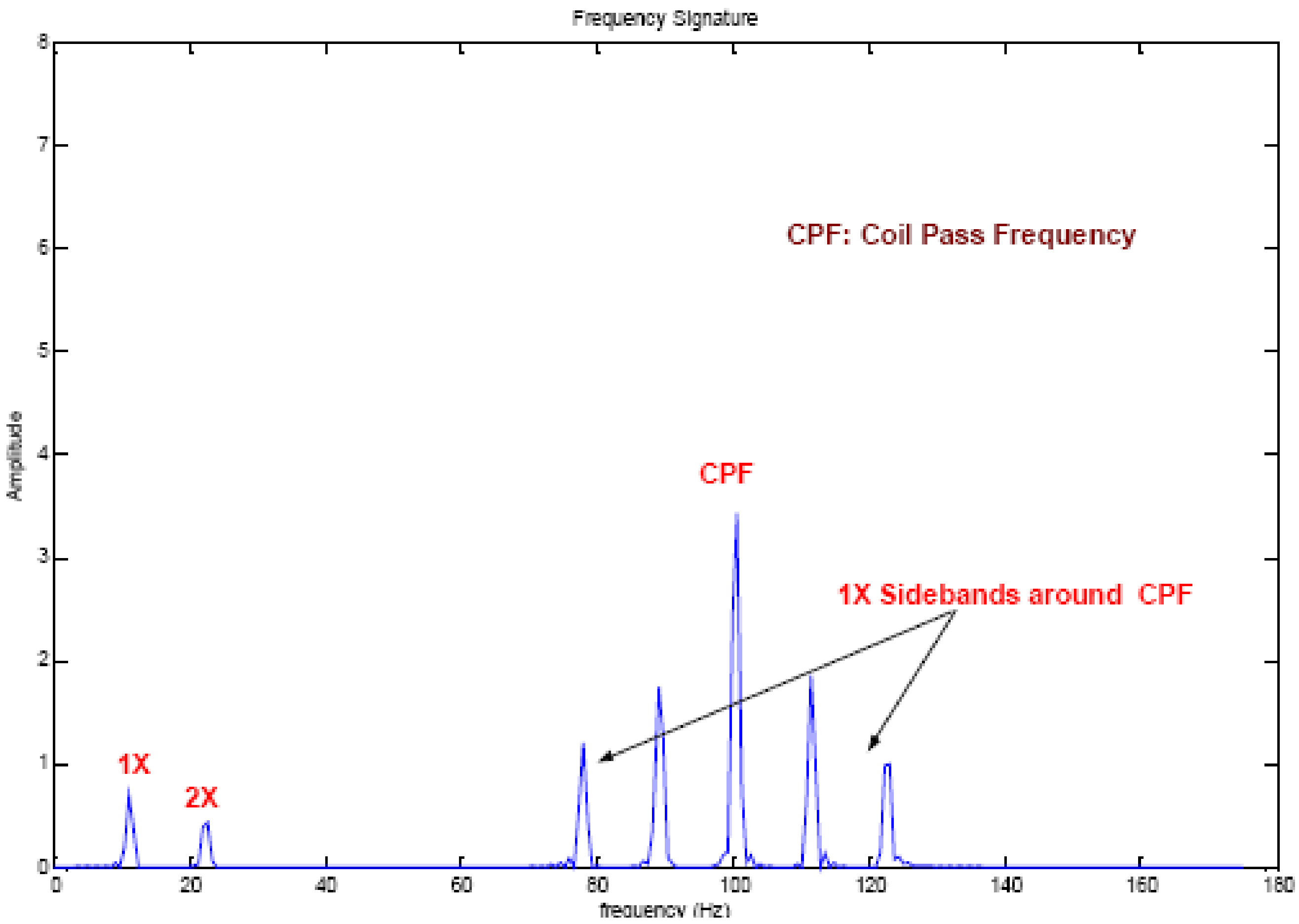
# Electric Motors

*Synchronous Motors*

- Loose stator coils in synchronous motors will generate fairly high vibration at Coil Pass Frequency (CPF)
- *CPF = # Stator Coils X RPM*
- *# Stator Coils = Poles X # Coils/Pole*
- The coil pass frequency will be surrounded by 1x RPM sidebands.

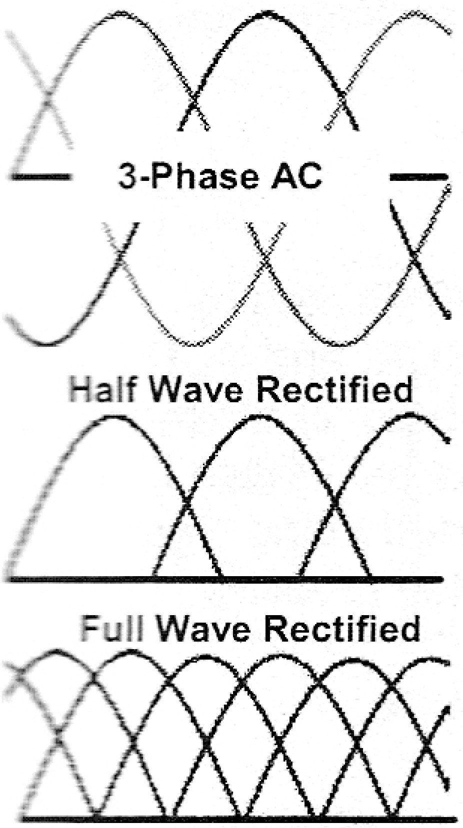
# Electric Motors

## Synchronous Motors (loose stator coils)

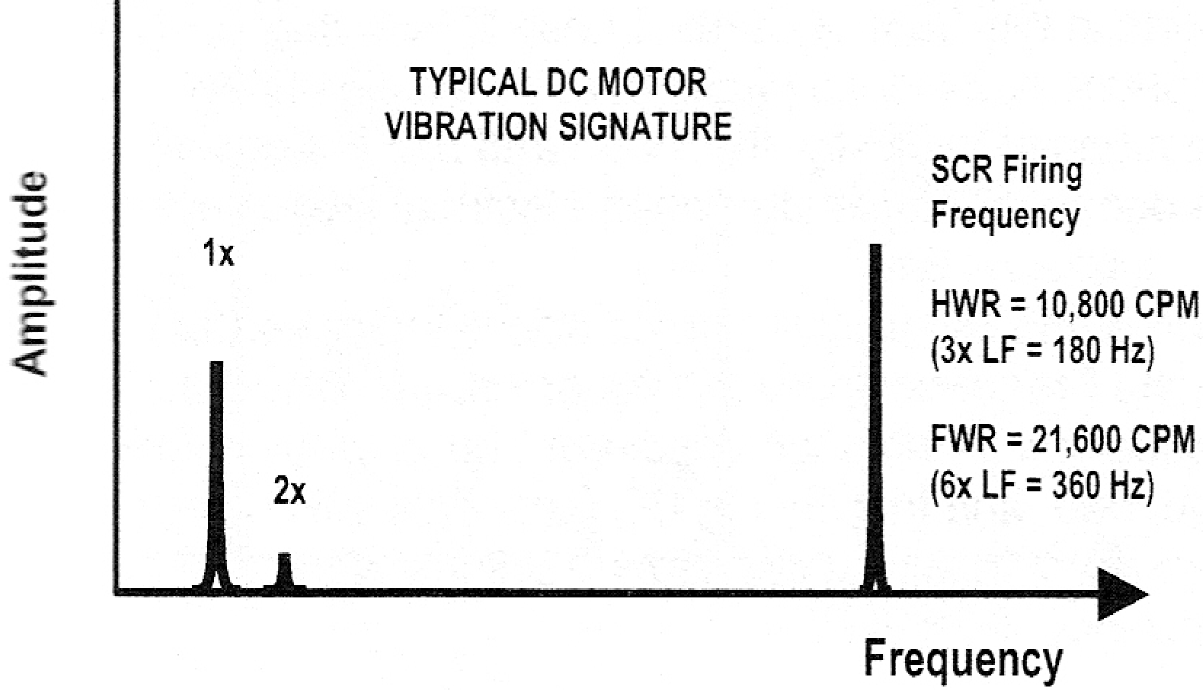


# Electric Motors

- DC Motors (Typical) – power electronics used to convert AC to DC waveforms with speed control.




SCR - Silicon Control Rectifier



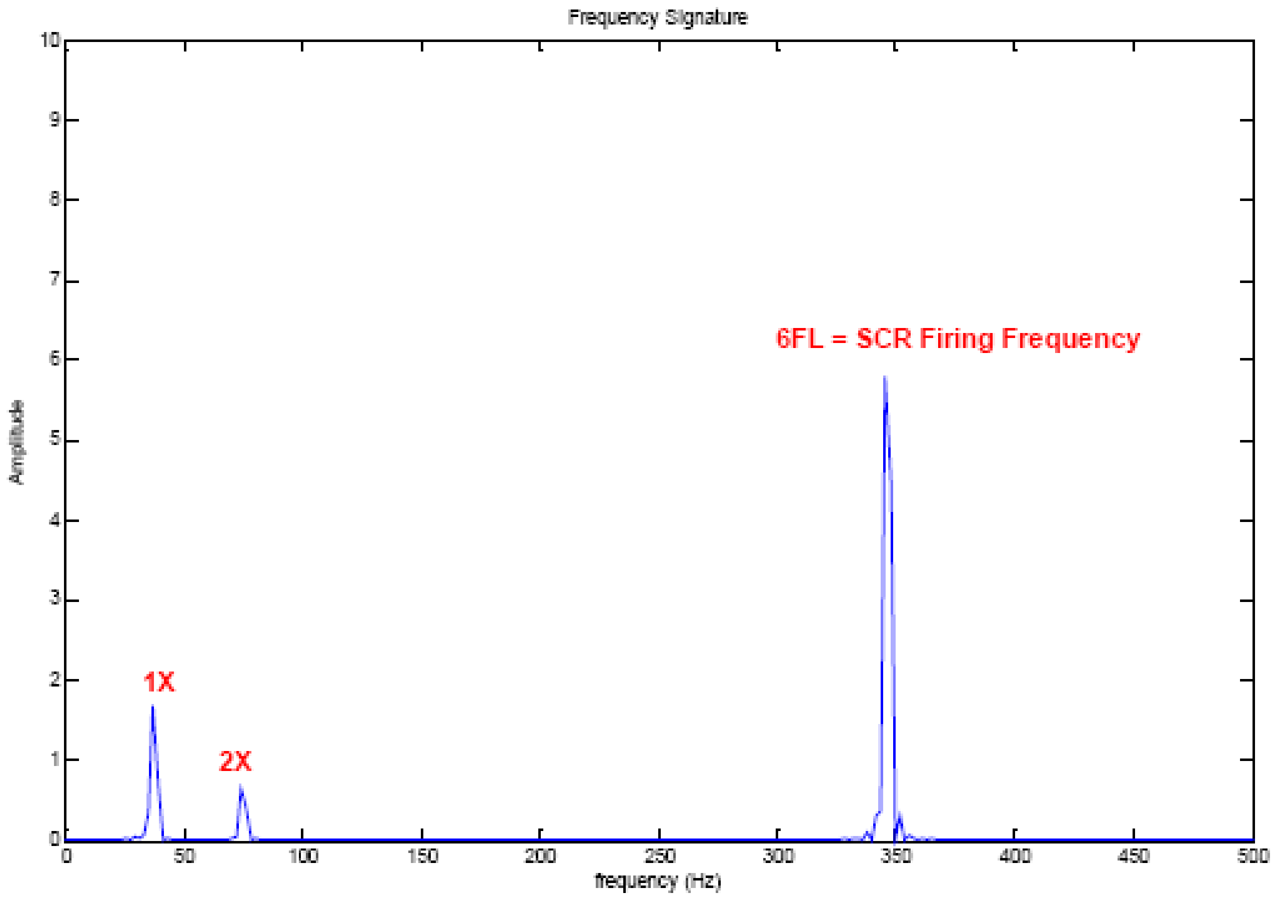
# Electric Motors

## *DC Motor Problems*

- DC motor problems can be detected by higher than normal amplitudes as SCR firing Frequency (6FL) and harmonics
- These problems include broken field windings, bad SCR's and loose connections
- Other problems including loose or blown fuses and shorted control cards can cause high amplitude peaks at 1X through to 5X line frequency (3,600 - 18,000 CPM).

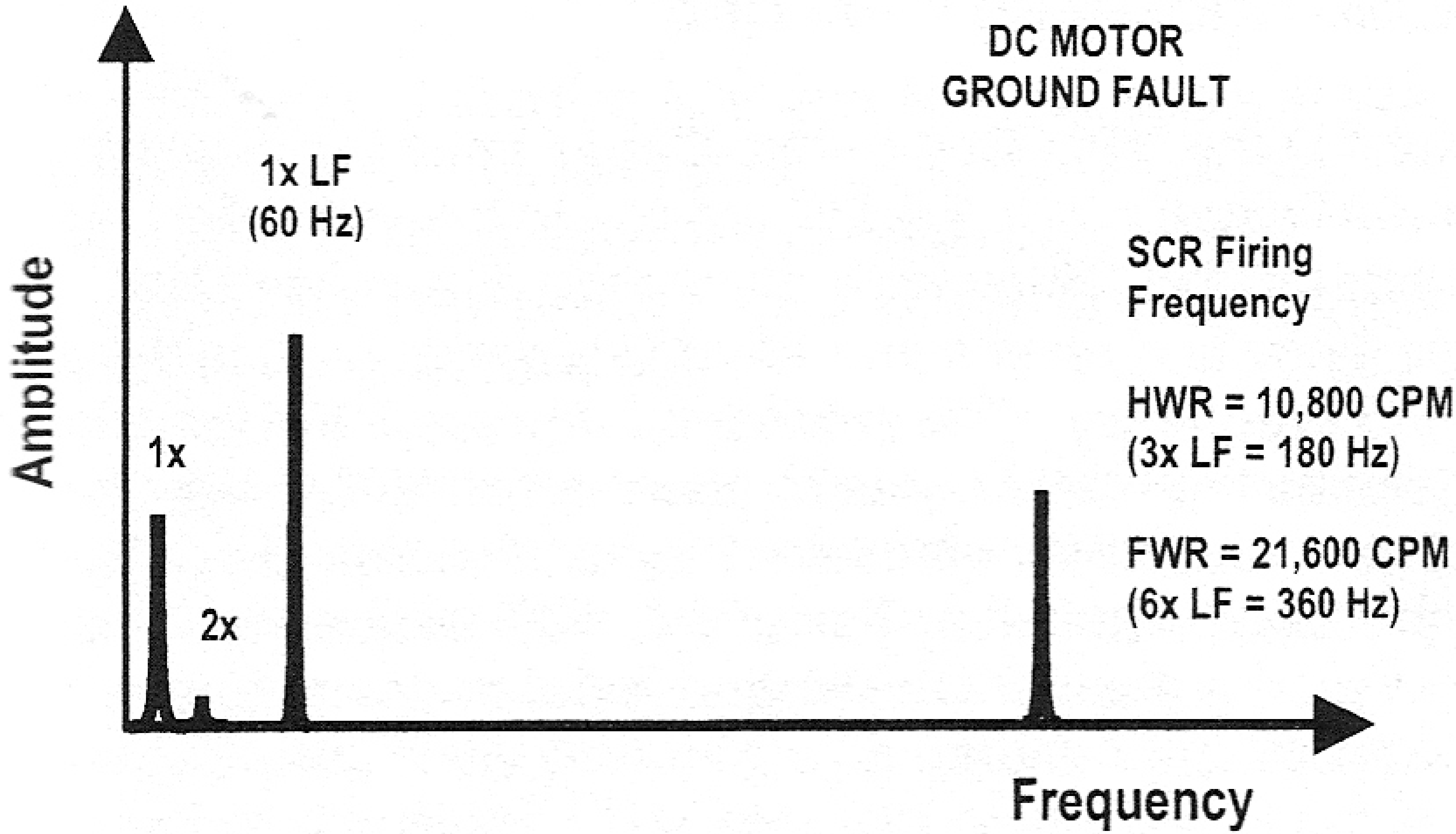
# Electric Motors

## DC Motors (broken field windings)



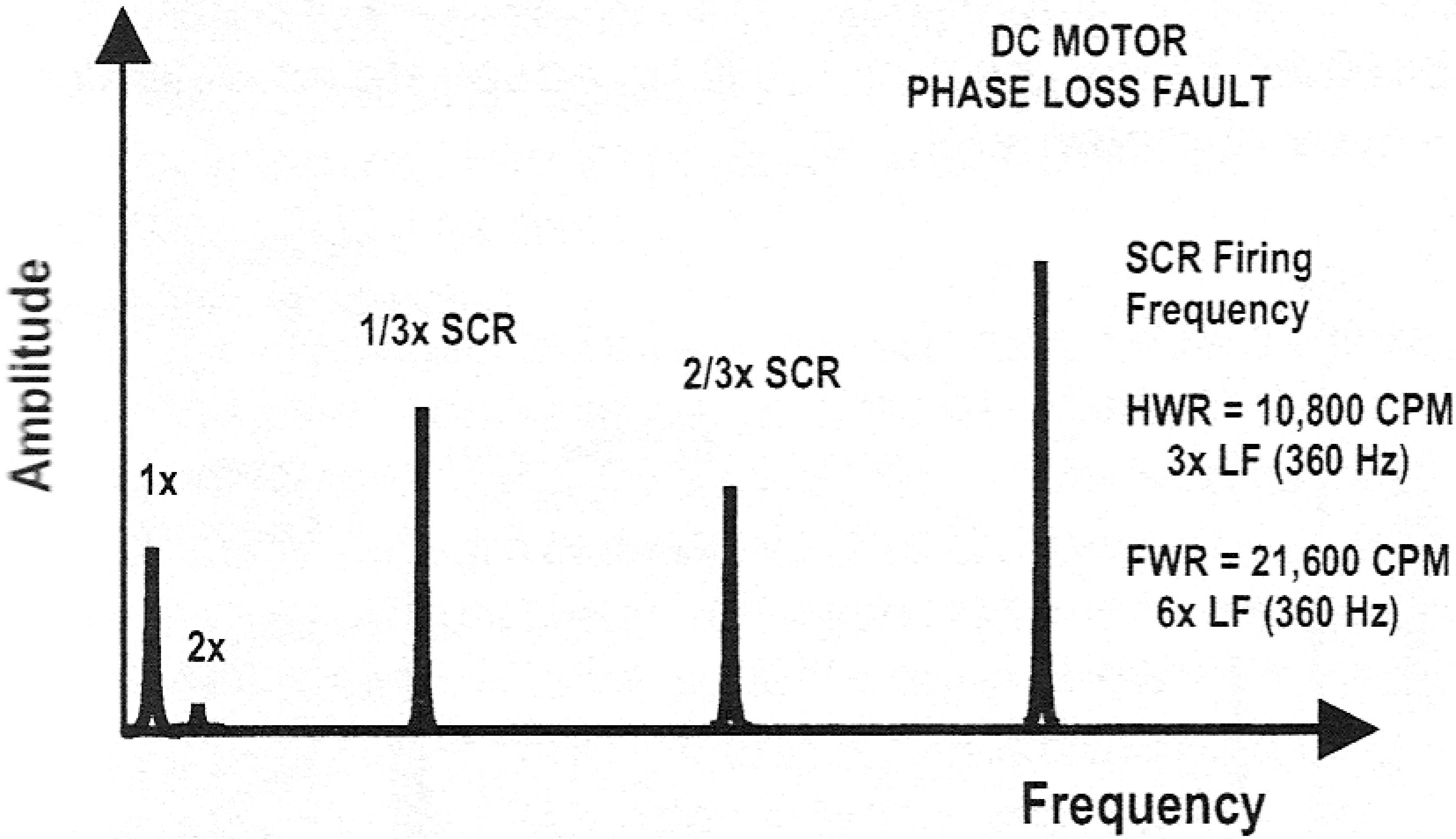
# Electric Motors

- DC Motors – Ground Fault



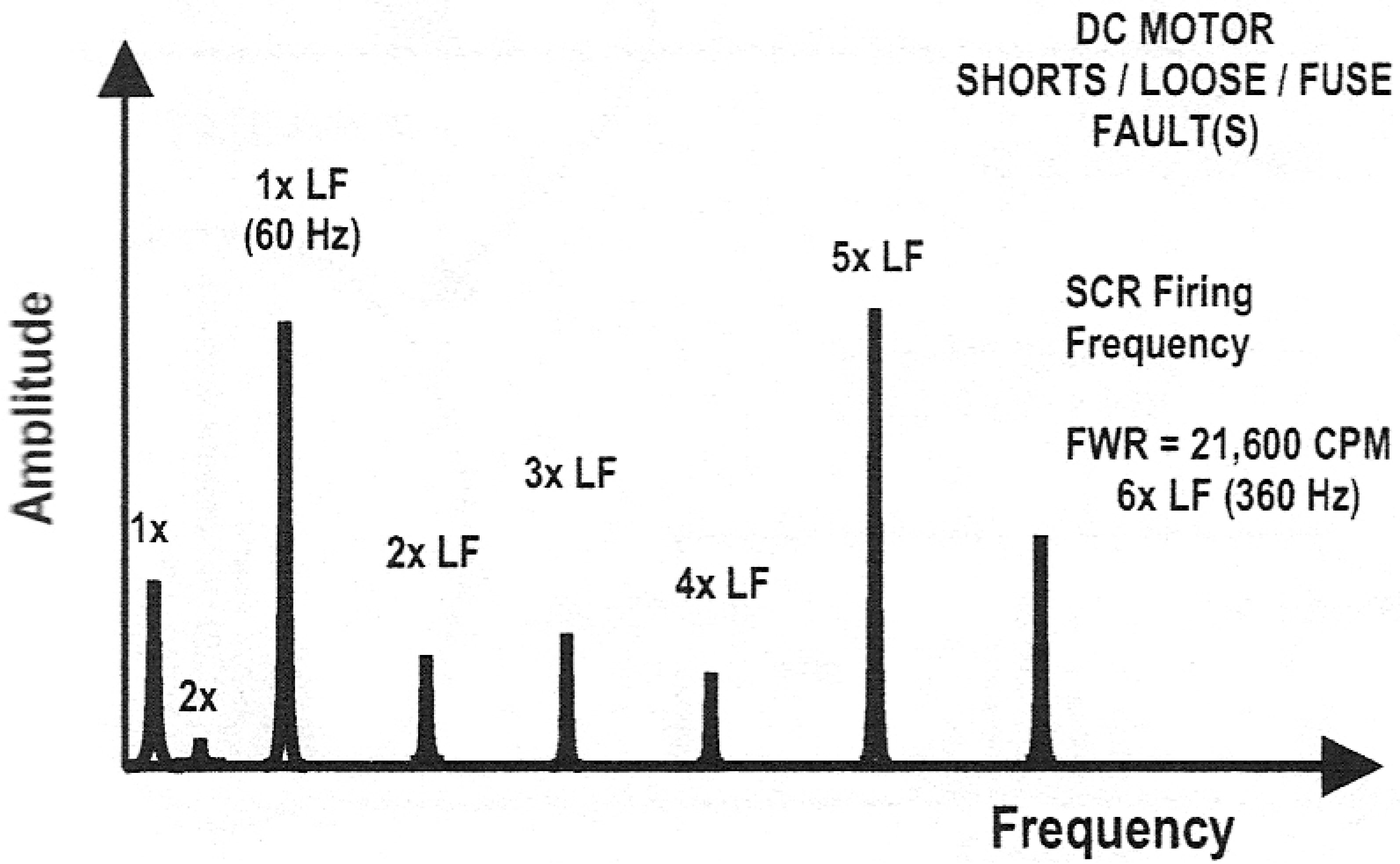
# Electric Motors

- DC Motors – Phase Loss Fault



# Electric Motors

- DC Motors – Shorts / Looseness / Fuse Faults



# Electric Motors

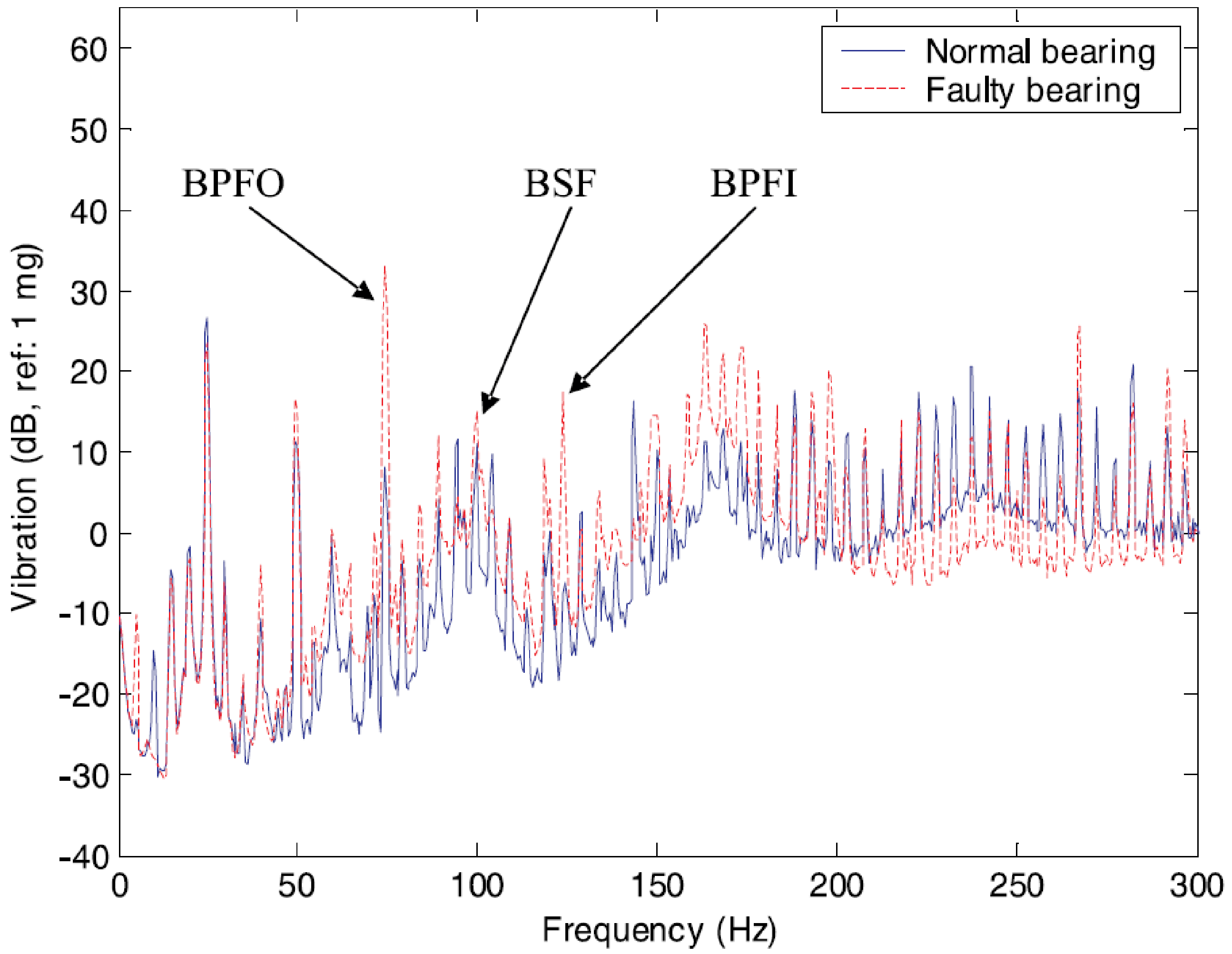



Figure 8. Spectral comparison of radial vibration signatures at 25 Hz and 0% load.

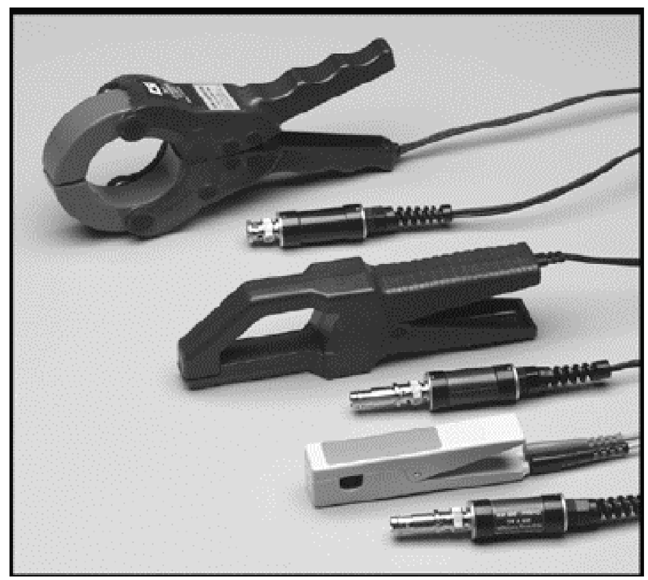
# Electric Motors

## Motor Current Analysis

- good for direct detection, diagnosis, prognosis
- Similar analysis techniques as applied in vibration signal analysis

Flux Coil

Current Transformers



# Electric Motors

*Flux Coil*

* **Benefits:**

åReduces safety concerns by not having to address live power leads.

åOn-line non-intrusive motor diagnostic tool.

åEasy to mount on the opposite drive end of motor.

åEliminates need for current clamp in most cases.

åDetection of electrical faults in ac induction motors.

# Electric Motors

*Flux Coil*

***Technical Description:**

åThe CSI Model 343 flux coil is designed
for use with
CSI machinery analyzers to detect flux
generated by
electric motors. Except for the initial
calibration and
possible verification, the use of the 343 flux
coil
eliminates the need for current clamp
measurements.
The flux coil captures flux signals which
provide an
electrical "quality" signature.

# Electric Motors

*Flux Coil*

***Technical Description cont.:**

åThis electrical signature is sensitive to conditions which alter the electrical characteristics of the motor, such as broken rotor bars, eccentricity, voltage imbalance between phases, and stator faults.

åFlux readings are acquired by consistent placement of the flux coil on the axial outboard end of the motor and automatically stored in the analyzer. Spectra of these measurements may be permanently stored, trended, or analyzed for alarms in CSI MotorView II software.

# Electric Motors

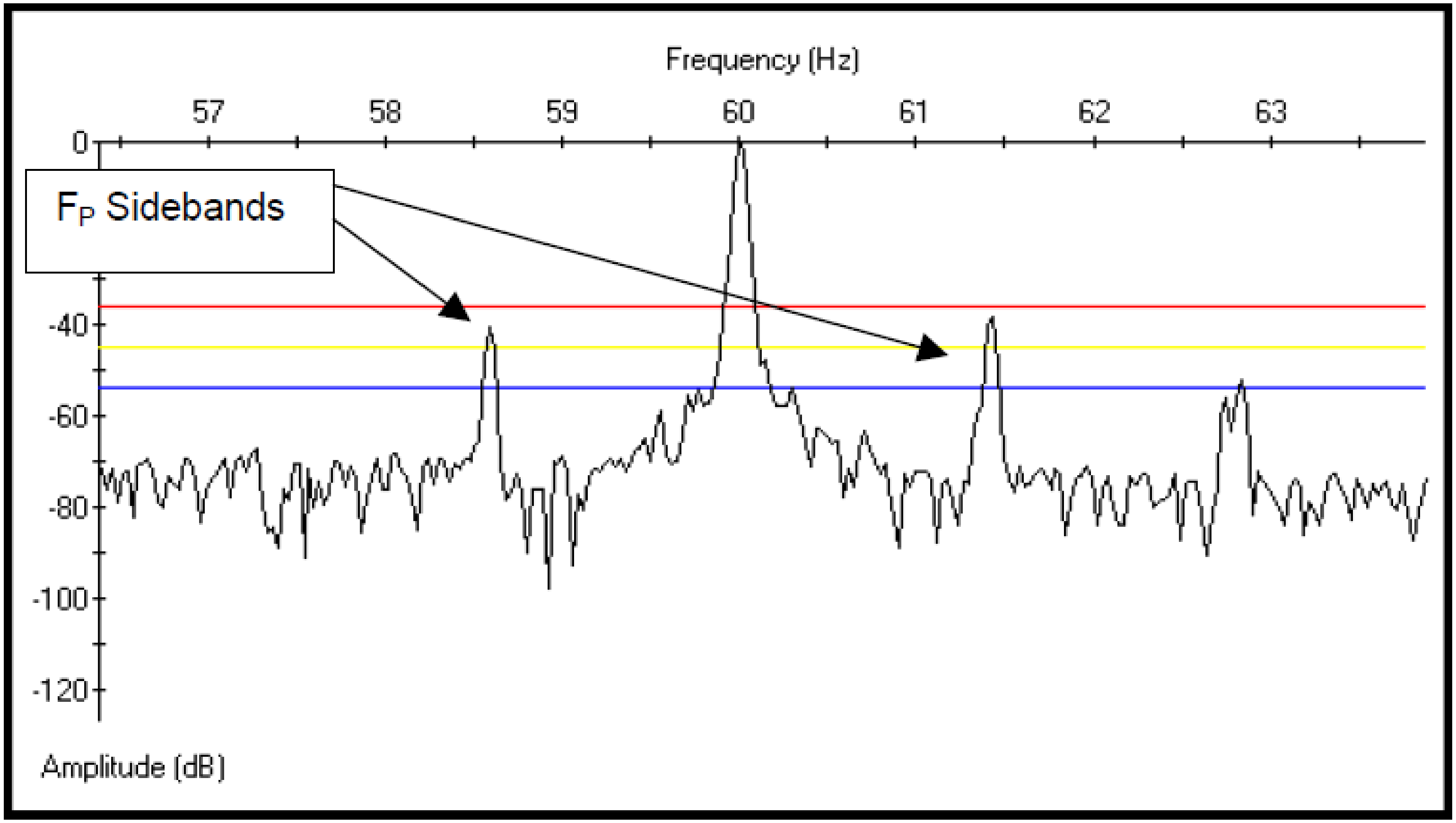



Figure 2: Spectrum of a Motor With Damaged Rotor

# Electric Motors

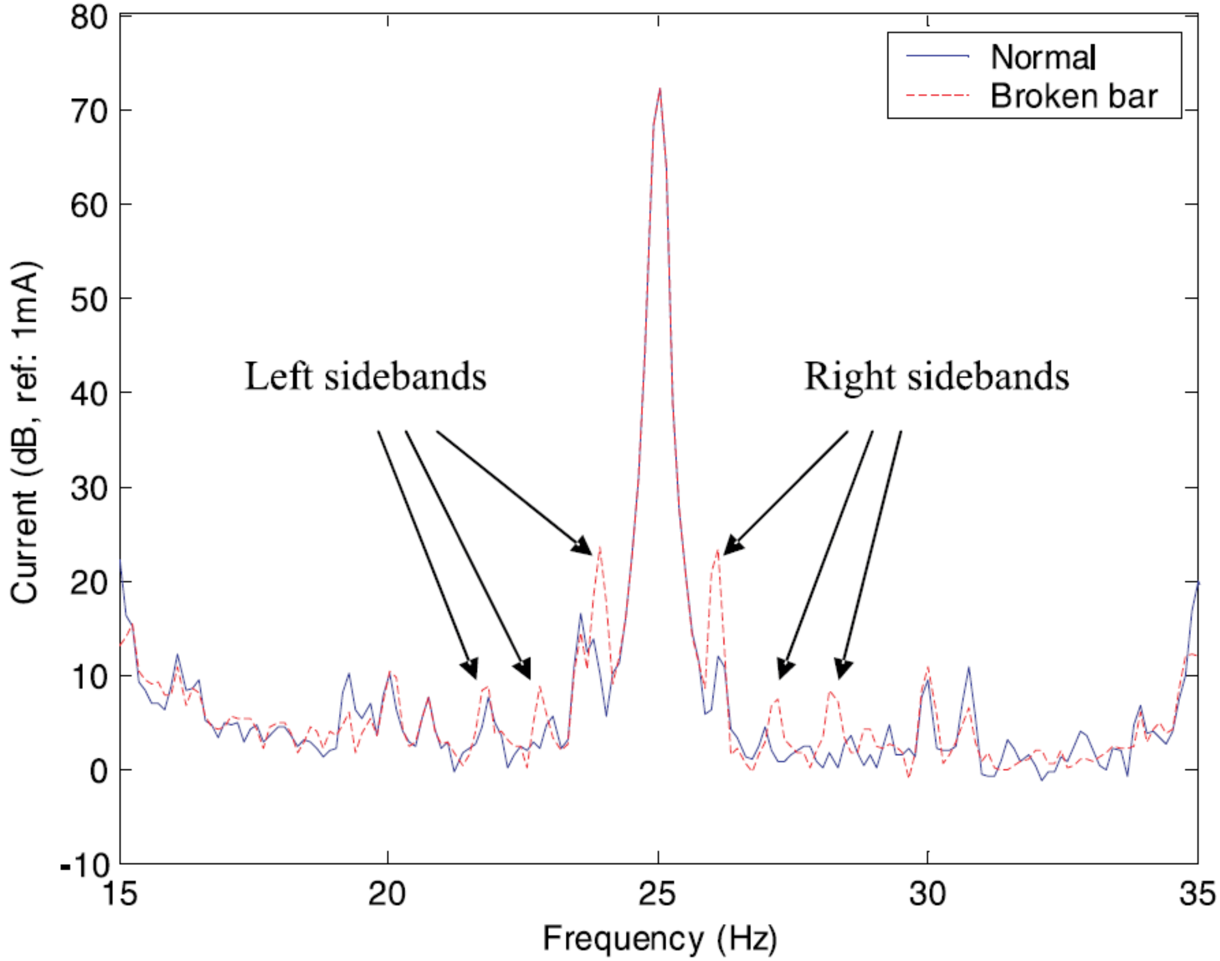



Figure 4. Current spectra of normal and faulty motors.

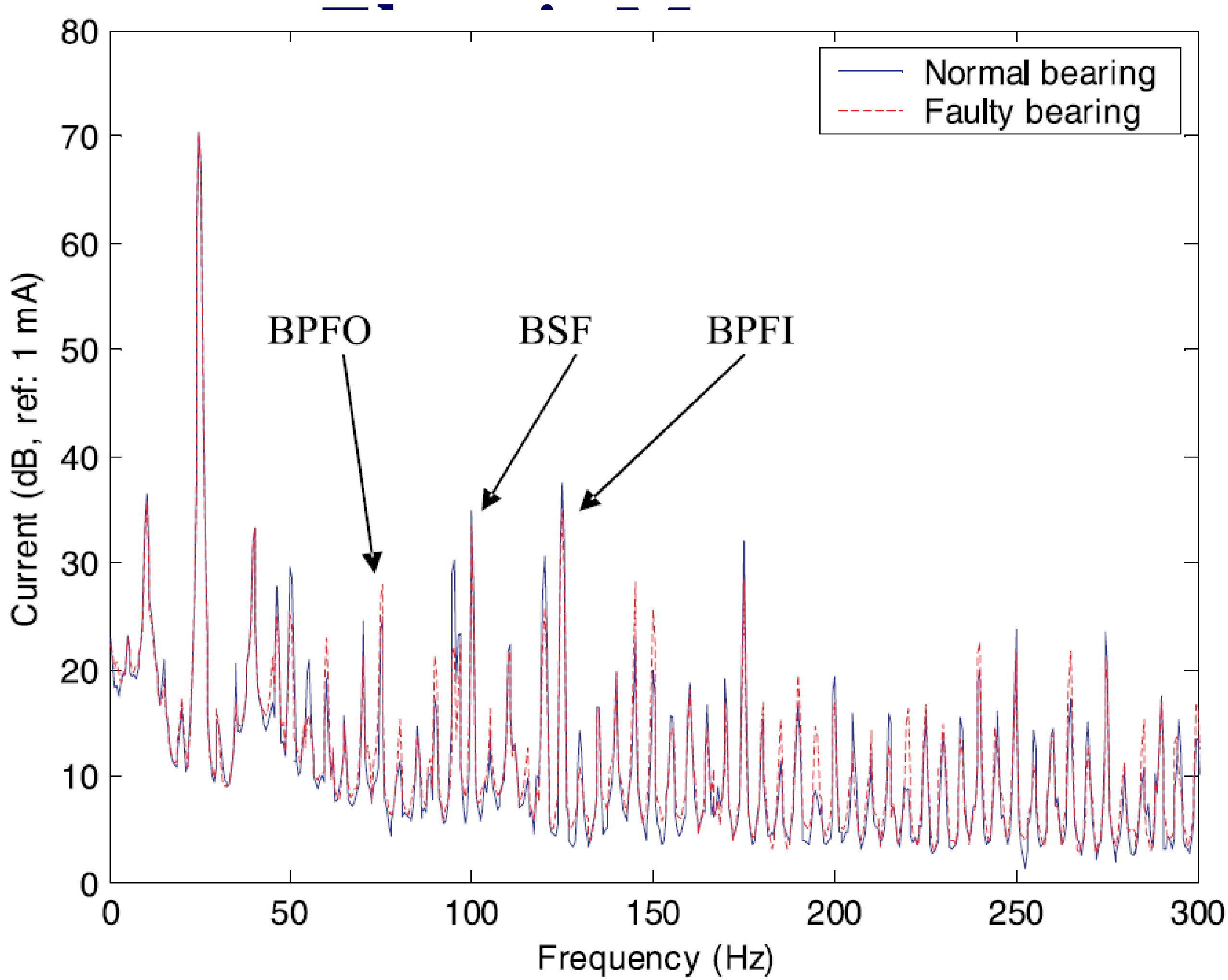
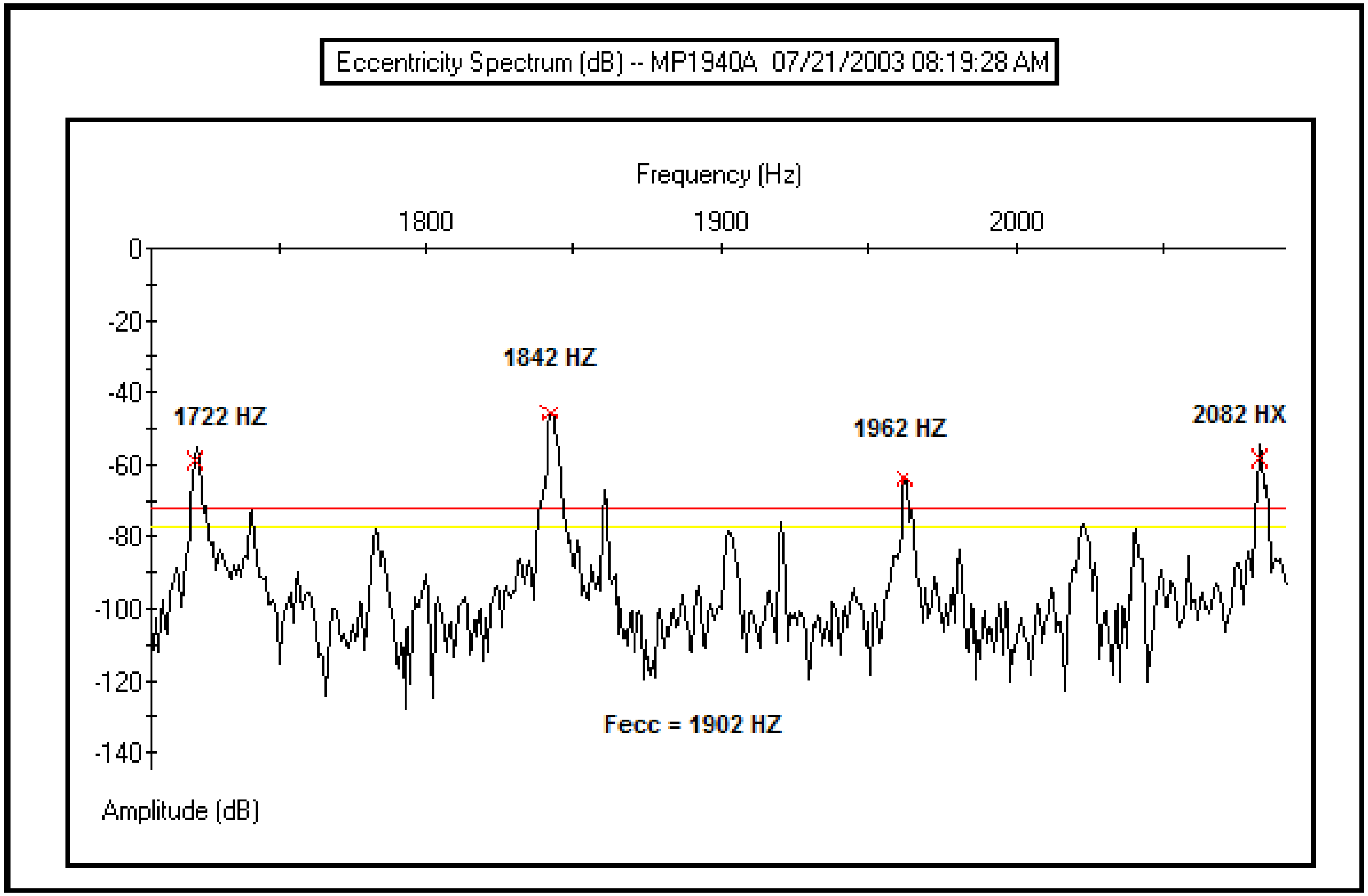



Figure 9. Spectral comparison of current signatures at 25 Hz and 0% load.

# Electric Motors




Current Spectrum of a Motor With Air Gap Eccentricity

# Rolling Element Bearings

Acoustic signal analysis

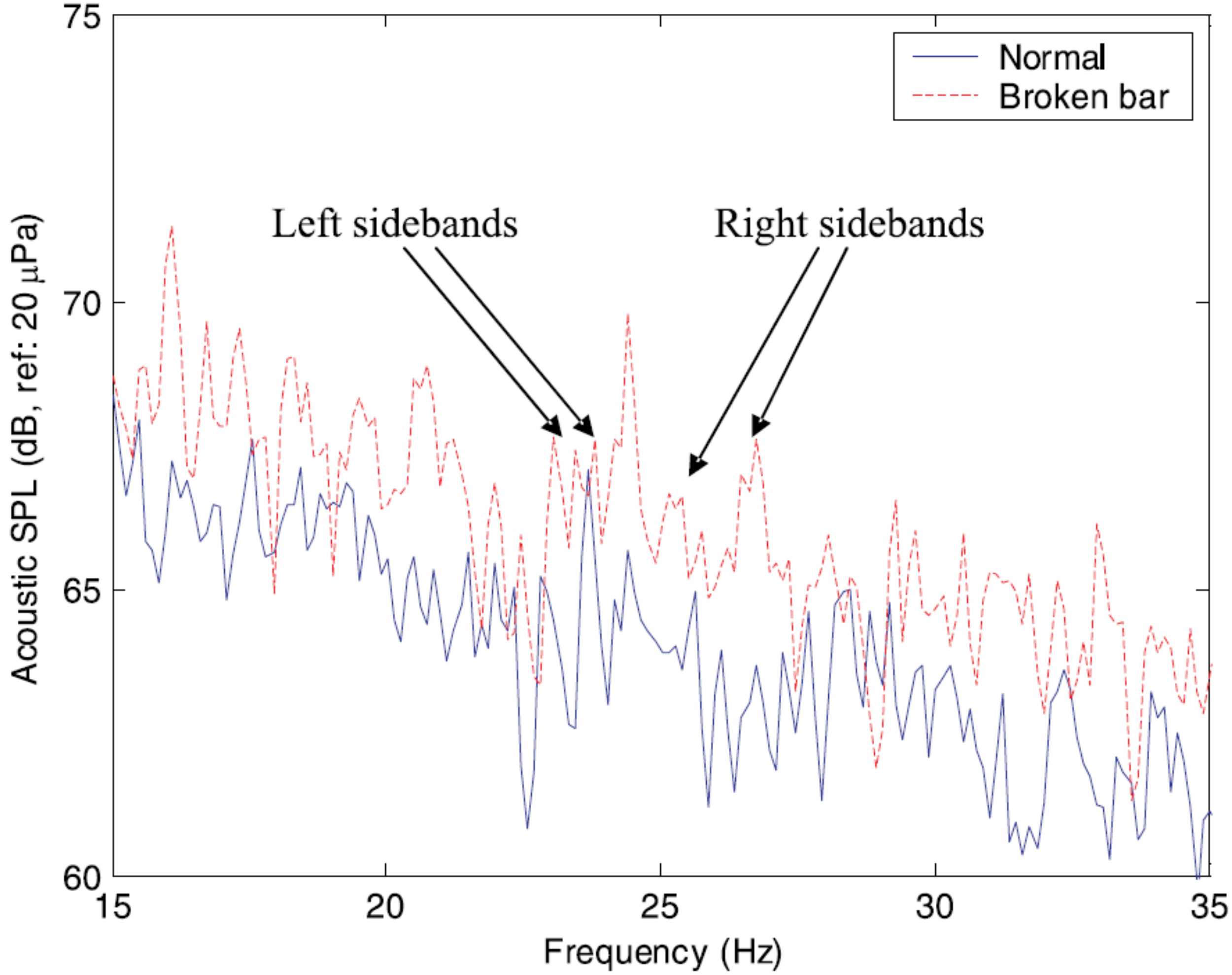



Figure 5. Acoustic spectra of normal and faulty motors.

# Fault Diagnostics Based on Machine Type

## STEAM / GAS TURBINES

Special attention because of the high speeds and temperatures involved

Because of the high speeds this type of machinery is usually designed lighter and less rigidly than other rotating machines

Problems on steam turbines are usually limited to looseness, unbalance, misalignment, soft foot, resonance, and rubs

# Steam and Gas Turbines

High-speed turbines and compressors are designed to closer tolerances than other types of machines and extra care is taken when balancing rotors

Excessive vibration can therefore lead to catastrophic failure very quickly

These machines also frequently operate above their first critical speed and sometimes between their second and third critical speeds

# Steam and Gas Turbines

At high-speed the rotor becomes quite flexible and the support bearings become very important in that they must provide the appropriate amount of damping

steam and gas turbines are supported on journal bearings

most monitoring and diagnostics work will be based solely on proximity probe signals

# Fault Diagnostics Based on Machine Type

## RECIPROCATING MACHINES

Reciprocating machines (gas and diesel engines, steam engines, compressors and pumps) all have one thing in common – a piston that moves in a reciprocating manner

These machines generally have high overall vibration levels and particularly strong responses at 1X and harmonics even when in good condition

# Reciprocating Machines

The vibrations are caused by compressed gas pressure forces and unbalance

Vibrations at ½X may be present in four stroke engines because the camshaft rotates at one-half the crankshaft speed

Many engines operate at variable speeds, which will allow the strong forcing functions to excite resonances of the components and the mounting structure (if not designed in a robust manner)

# Reciprocating Machines

Excessive vibrations in reciprocating machines usually occur due to operational problems (misfiring, piston slap, compression leaks, and faulty fuel injection)

These problems result in elevated ½X vibrations if only one cylinder is effected and a decrease in efficiency and power output

Gear and bearing problems may also occur in reciprocating machines, but characteristic defect frequencies for these faults are significantly higher

# Next Time

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Types
- Automatic Diagnostics Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods