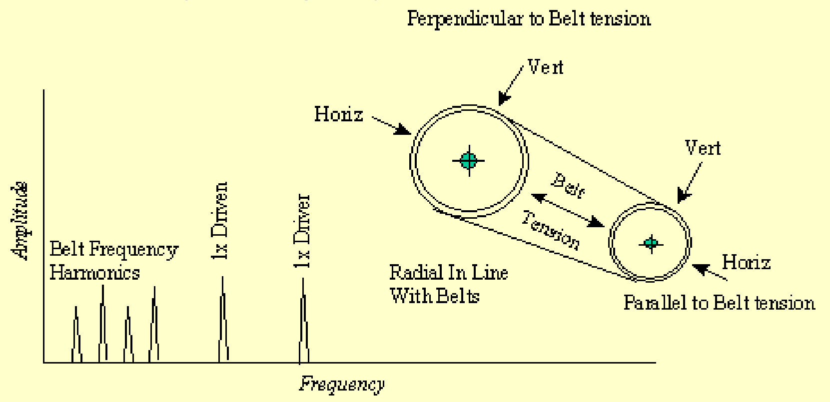
A Quick Guide to Vibration Diagnostics of Rotating Machinery

Belt Problems

Worn, Loose or Mismatched Belts

- Belt frequencies are below the RPM of either the motor or the driven machine.
- When they are worn, loose or mismatched, they normally cause 3 to 4 multiples of belt frequency.
- Often 2 x belt frequency is the dominant peak.
- Amplitudes are normally unsteady, sometimes pulsing with either driver or driven RPM.
- On timing belt drives, wear or pulley misalignment is indicated by high amplitudes at the timing belt frequency.

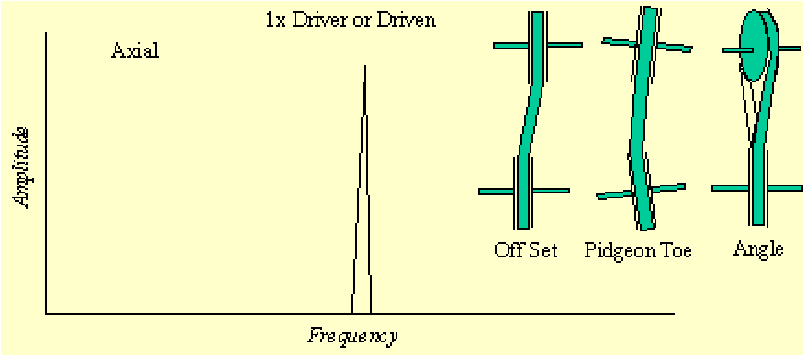


Belt frequency
= $\pi D \times RPM / L$

D: Sheave diameter
L: Belt length
RPM: Sheave speed

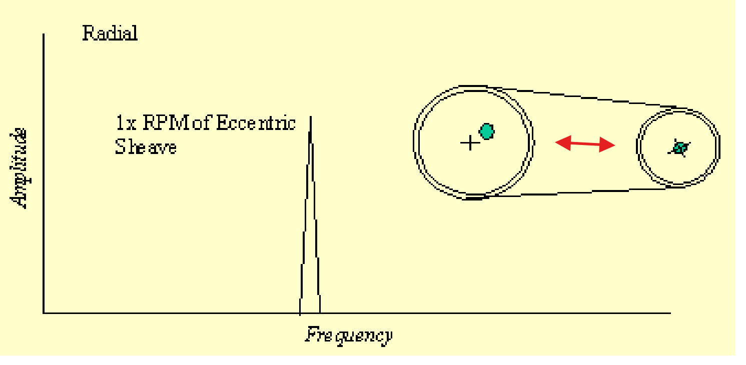
Belt / Sheave Misalignment

- Misalignment of sheaves produces high vibration at 1x RPM predominantly in the axial direction and axial harmonics of the fundamental belt frequency
- The ratio of amplitudes of driver to driven RPM depends on where the data is taken as well as on relative mass and frame stiffness
- Often with sheave misalignment, the highest axial vibration will be at the fan RPM



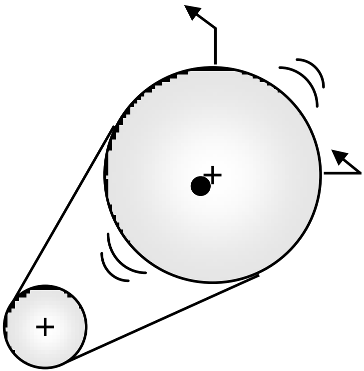
Eccentric Sheaves, Sheave Run-out

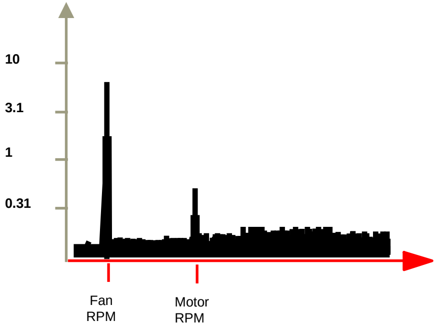
- Eccentric/ unbalanced sheaves cause high vibration at 1 x RPM of this sheave.
- The amplitude is normally highest in line with the belts, and should show up on both driver and driven bearings
- This can be checked by removing the belts and measuring again
- It is sometimes possible to balance eccentric sheaves by attaching washers to taper lock bolts
- However, even if balanced, the eccentricity will still induce vibration and reversible fatigue stresses in the belt



ECCENTRIC SHEAVES

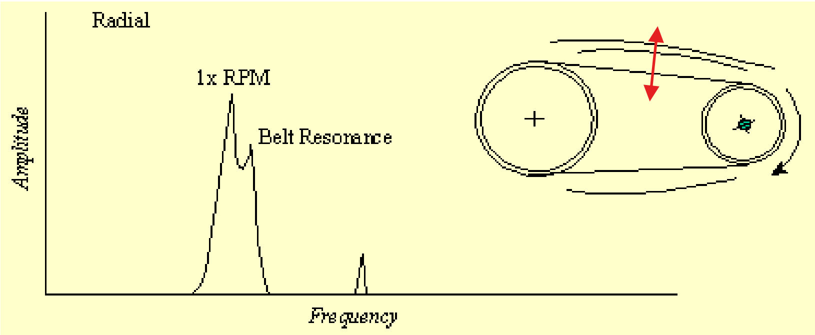
- Center of rotation different from geometrical center
- The eccentric rotor will produce high vibration at the rotation speed.
- The phase will be the same in both horizontal and vertical direction.
- If you try to balance an eccentric rotor, you may reduce the vibration readings in one direction, but the readings will increase in the other.





Belt Resonance

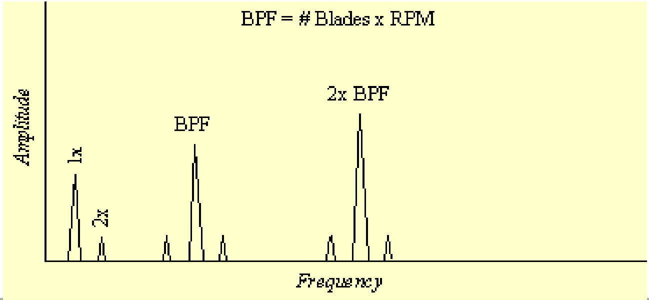
- Belt resonance can cause high amplitudes if the belt natural frequency should happen to approach or coincide with either the motor or the driven machine RPM
- Belt natural frequency can be altered by either changing the belt tension or the belt length
- Can be detected by tensioning and the releasing belt while measuring response on sheaves or bearings

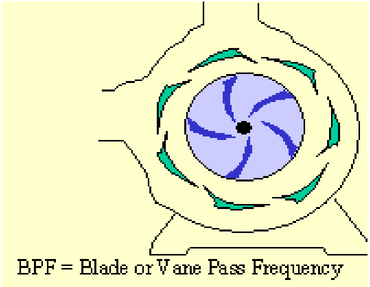


Pump Problems

Hydraulic Forces : Blade Pass & Vane Pass

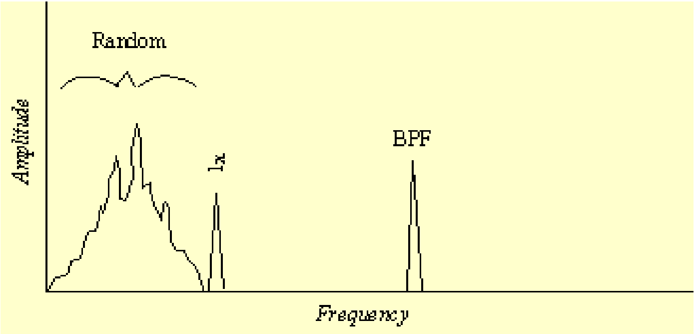
- Blade pass frequency (BPF) = number of blades (or vanes) x RPM.
- This frequency is inherent in pumps, fans and compressors and normally does not present a problem.
- However, large amplitude BPF and harmonics can be generated in the pump if the gap between the rotating vanes and the stationary diffusers is not kept equal all the way round.
- Also, BPF(or harmonics) sometimes coincide with 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. Also, high BPF can be caused by abrupt bends in line work (or duct), obstructions which disturb the flow path, or if the pump or fan rotor is positioned eccentrically within the housing.





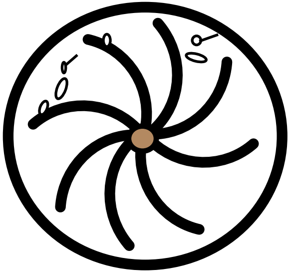
Hydraulic & Aerodynamic Forces: Flow Turbulence

- Flow turbulence often occurs in blowers due to variations in pressure or velocity of the air passing through the fan or connected line work.
- This flow disruption causes turbulence which will generate random, low frequency vibration, typically in the range of 20 to 2000 CPM.

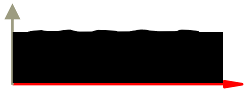


CAVITATION

- Cavitation is caused by the collapse of small bubbles that occurs during local boiling at certain condition of the fluid (low dynamic pressure)
- The Collapses are short in time and thus wide in frequency.
  - The resonances are exited throughout the spectrum
  - Specially high frequencies are exited
  - In envelope spectra an increase of the background level with no distinct lines are seen.



CPB Spectrum



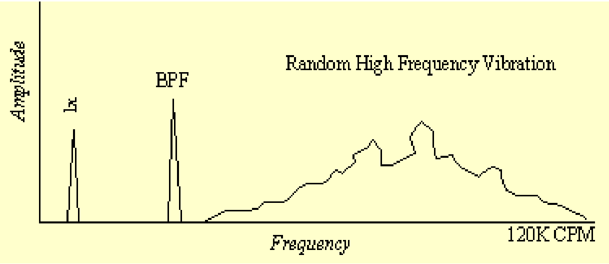
Envelope Spectrum

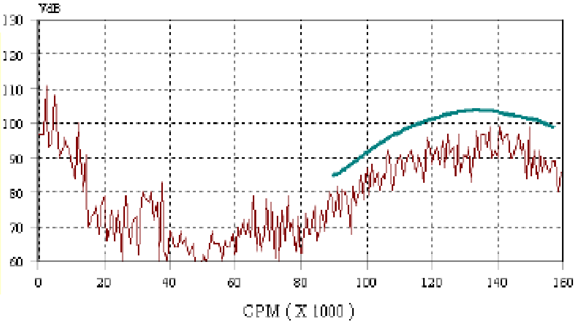
CAVITATION

- The faster a fluid travels by an object the lower the pressure will be, this phenomenon is well known as Bernoullis law, and it is the reason that aero planes can fly and turbo machines are working.
- The lower the pressure, the lower the boiling temperature of water.
- In some instances the water of a pump may start boiling locally as a result of the local fluid speed will decrease local dynamic pressure and hence decreased the boiling point below the fluid temperature.
- When the local pressure increases again the small bubbles formed in the boiling process collapses very rapidly.
- The rapid collapse causes shock pulses which may be strong enough to break apart fragments of metal on the location it occurs - cavitation wear.
- The collapsing bubbles also induce shock waves which are transferred through the structure.
- Since the pulses are very short, they have a very high frequency content, and they will excite resonances throughout the spectrum range.

Cavitation

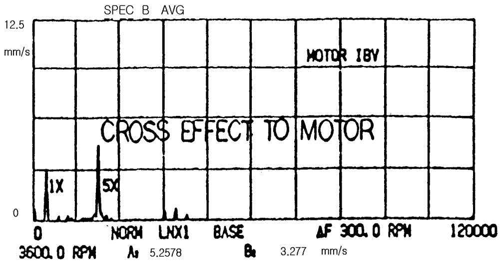
- Cavitation normally generates random, higher frequency broadband energy which is sometimes superimposed with blade pass frequency harmonics.
- Normally indicates insufficient suction pressure (starvation).
- Cavitation can be quite destructive to pump internals if left uncorrected.
- It can particularly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



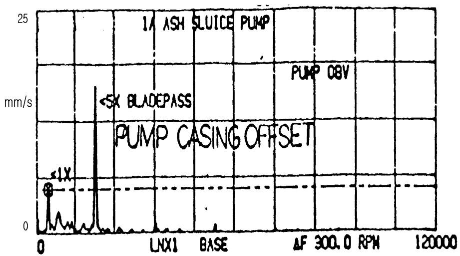


Unsuitable Pump Assembly

- Excessive vibration at Ash Sluice pump-motor (3600RPM)
  - Vane passing frequency component (5X) : 16.764 mm/s
  - Rotating frequency component (1X) : 2.54 mm/s
  - Cause: Casing distortion during assembly after overhaul



Motor vibration

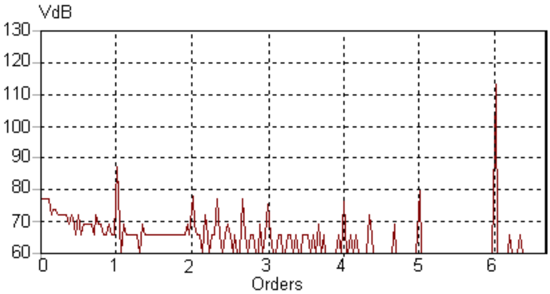


Sluice pump vibration

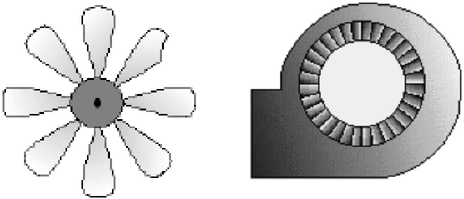
Fan Problems

Fan

- Most fans are either axial flow propeller-type fans, or are centrifugal type
- Fans, especially when they are handling particle-laden air or gas, are prone to uneven buildup of detritus on the blades.
- This causes imbalance, and should be corrected as soon as it is diagnosed.
- If any of the blades become deformed, cracked, or broken, the vibration peak of blade pass frequency will increase in level, and if there are many blades, sometimes 1X sidebands will appear around the blade pass frequency.



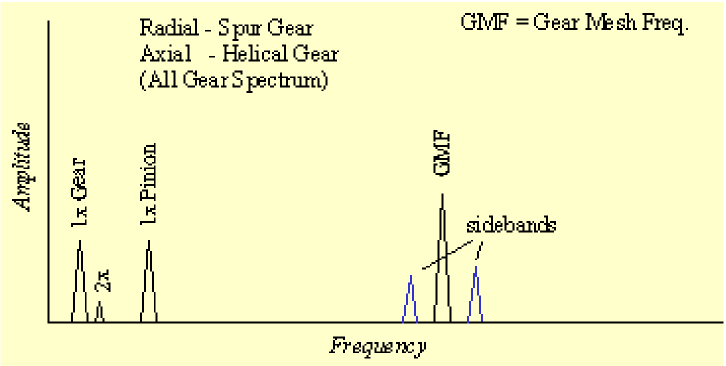
Six-Bladed Axial Fan



Gear Problems

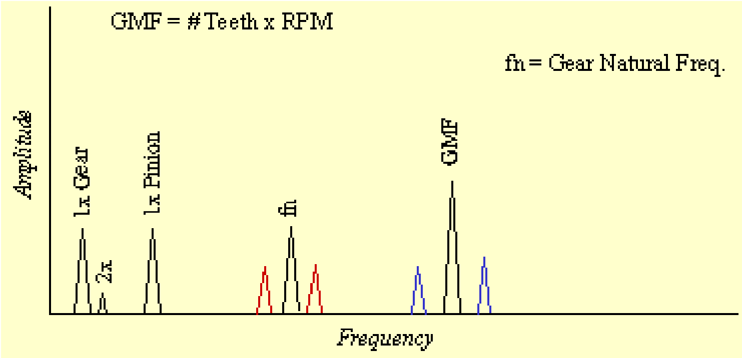
Normal Gear Spectrum

- Normal spectrum shows 1x and 2x RPM, along with gear mesh frequency (GMF)
- GMF commonly will have running speed sidebands around it relative to the shaft speed which the gear is attached to.
- All peaks are of low amplitude and no natural gear frequencies are excited.



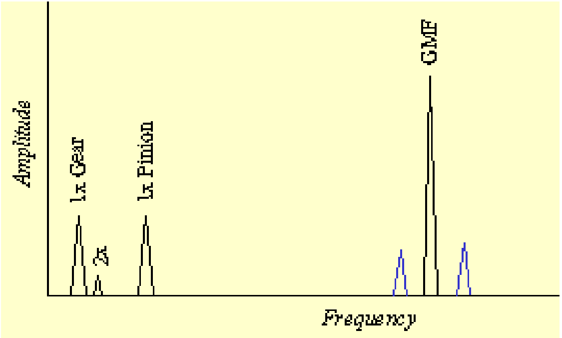
Gear Tooth Wear

- A key indicator of gear tooth wear is excitation of the Gear Natural Frequency, along with sidebands around it spaced at the running speed of the bad gear
- Gear mesh frequency (GMF) may or may not change in amplitude, although high amplitude sidebands surrounding GMF usually occur when wear is noticeable
- Sidebands may be a better wear indicator than GMFs themselves.



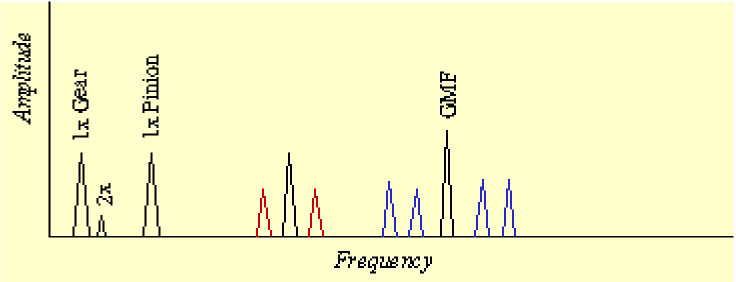
Tooth Load

- Gear mesh frequencies are often very sensitive to load.
- High GMF amplitudes do not necessarily indicate a problem, particularly if sideband frequencies remain low and no gear natural frequencies are excited
- Each analysis should be performed with the system at maximum operating load



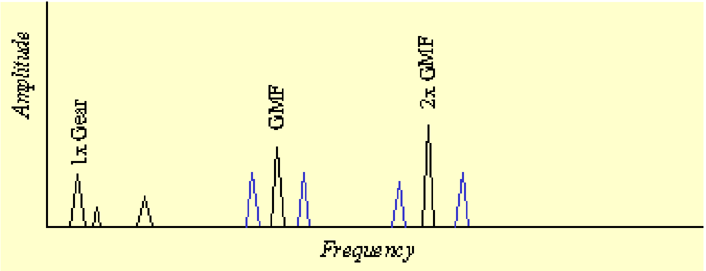
Gear Eccentricity & Backlash

- Fairly high amplitude sidebands around GMF often suggest gear eccentricity, backlash or non-parallel shafts which allow the rotation of one gear to "modulate" the running speed of the other.
- The gear with the problem is indicated by the spacing of the sideband frequencies
- Improper backlash normally excites GMF and gear natural frequencies, both of which will be sidebanded at 1x RPM.
- GMF amplitudes will often decrease with increasing load if backlash is the problem



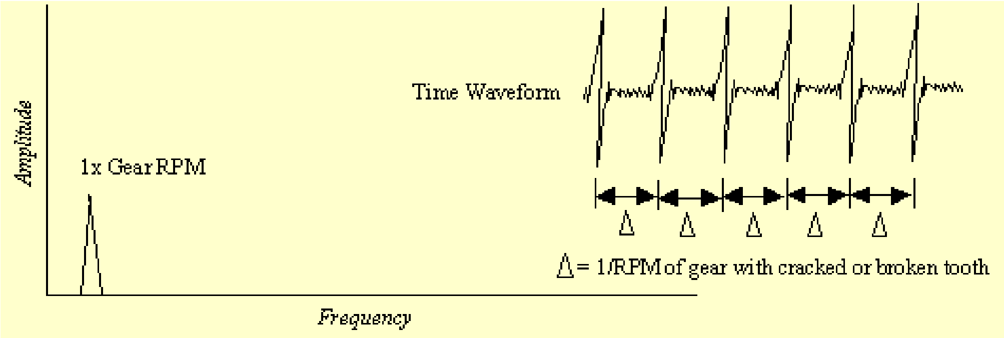
Gear Misalignment

- Gear Misalignment almost always excites second order or higher GMF harmonics which are sidebanded at running speed.
- Often will show only small amplitude 1x GMF, but much higher levels at 2x or 3x GMF
- Important to set the F_{max} high enough to capture at least 2 GMF harmonics if the transducer has the capability.



Cracked or Broken Gear Tooth

- A cracked or broken tooth will generate a high amplitude 1x RPM of this gear, plus it will excite the gear natural frequency (f_n) sidebanded at its running speed
- It is best detected in time waveform which will show a pronounced spike every time the problem tooth tries to mesh with teeth on the mating gear
- Time between impacts (Δ) will correspond to 1/speed of gear with the problem
- Amplitudes of impact spike in time waveform will often be much higher than that of 1x gear RPM in FFT.



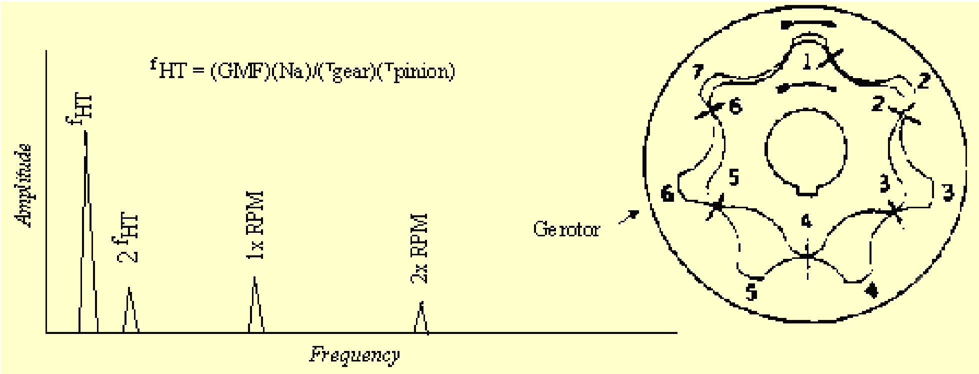
Hunting Tooth Problems

- Hunting Tooth Frequency (HTF) is particularly effective for detecting faults on both the gear and the pinion that might have occurred during the manufacturing process or due to mishandling.
- It can cause quite a high vibration, but since it occurs at low frequencies, predominantly less than 600 CPM, it is often missed.
- A gear set with this tooth repeat problem normally emits a "growling" sound from the drive.
- The maximum effect occurs when the faulty pinion and gear teeth both enter mesh at the same time (on some drives, this may occur once every 10 or 20 revolutions, depending on the f_{HT} formula).

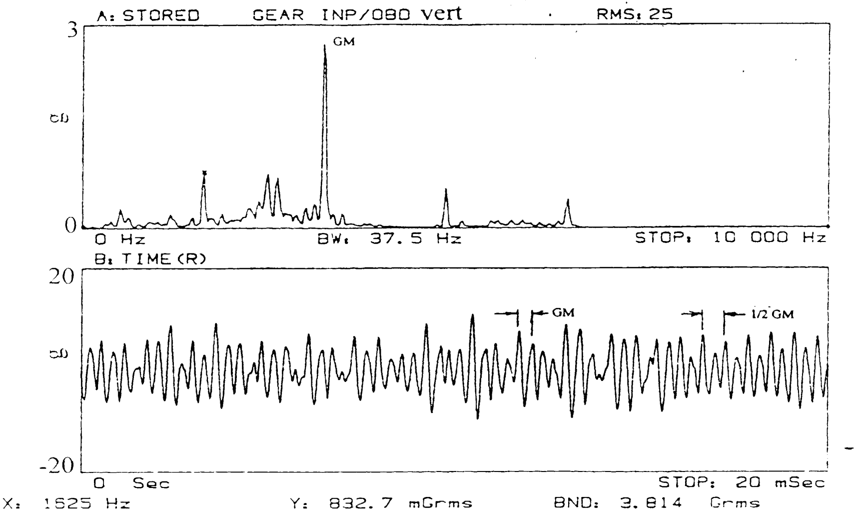
$$f_{HT} = GMF \times N_a / (T_{Gear} \times T_{Pinion})$$

- T_{Gear}, T_{Pinion} = number of teeth on the gear and pinion, respectively.
- N_a = number of unique assembly phases for a given tooth combination which equals the product of prime factors common to the number of teeth on each gear

Hunting Tooth Problems



Case History : Tooth Wear

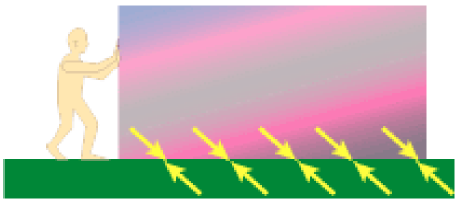


Vibration due to gear wear in reduction gear box

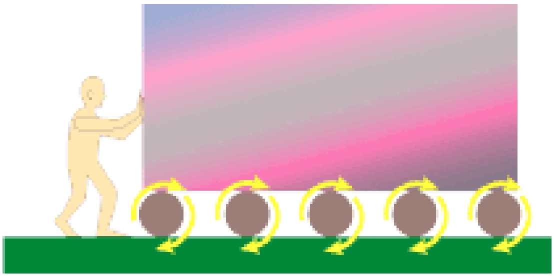
Bearing Problems

What's Bearing ?

- A part which supports a journal and in which the journal revolves (ISO 1925)
- A mechanical element which inserted rolling elements or lubrication between two bodies with relative motion for reducing the friction



Without rolling elements or lubrication

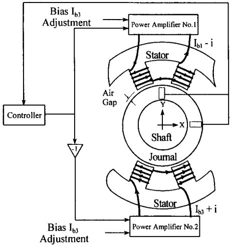


With rolling elements or lubrication

Bearing Types

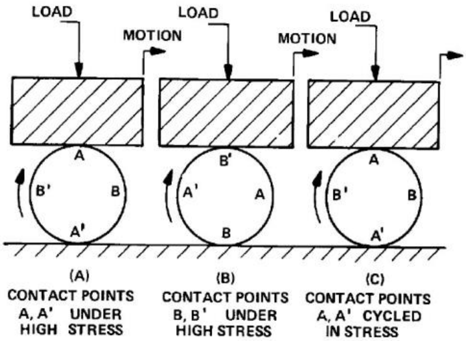
Bearings

- **ROLLING ELEMENT**
  - Ball
  - Roller
  - Spherical
- **FLUID FILM**
  - Hydrodynamic
  - Hydrostatic
  - Hybrid
- **ACTIVE CONTROL**
  - Magnetic
  - Piezoelectric
  - Electrorheological

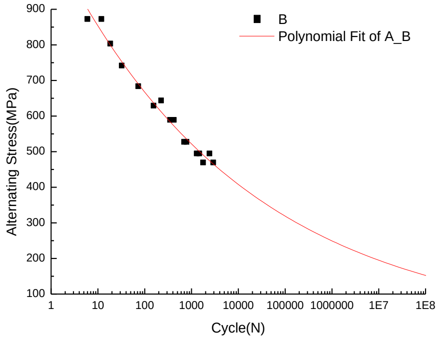


Rolling Element Bearings

Merit	Demerit
• Standardization, compatibility • Simple structure, easy repair & check • Small starting friction torque • support radial/axial loads simultaneously	• Limited life span due to fatigue failure of rolling elements • Poor damping capacity • Limited load support capacity • For small/ low speed machinery



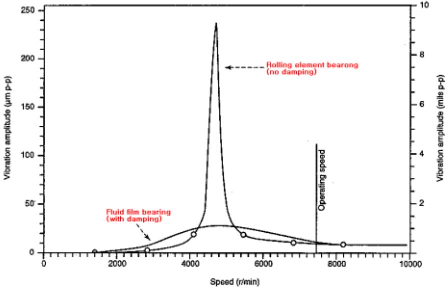
Fatigue failure of rolling bearing



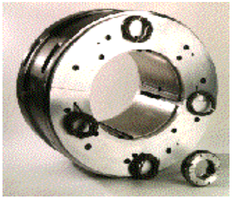
S-N curve

Fluid Film Bearings

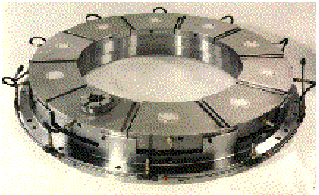
Merit	Demerit
• High load capacity • Large/high speed M/C • Strong impact • Good damping • Low noise • Long life	• Oil whip/ whirl • Complex structure (oil supplying system) • Week temperature • Expensive



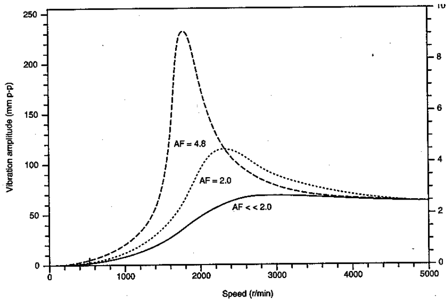
Effect of damping



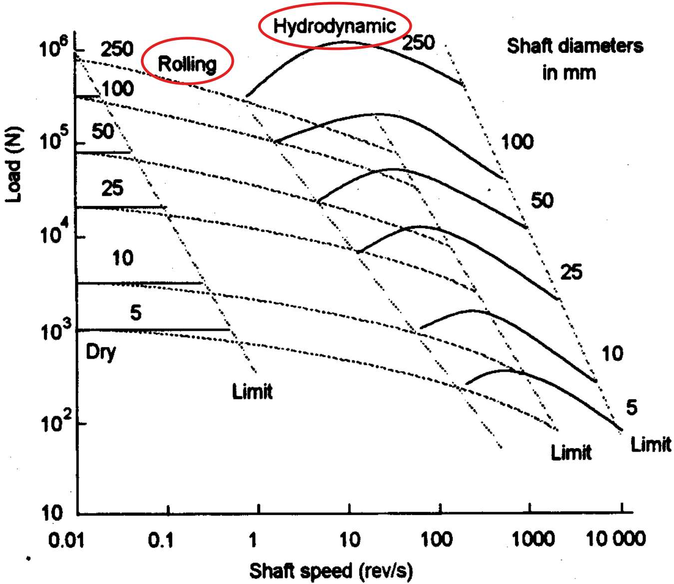
Journal bearing



Thrust bearing

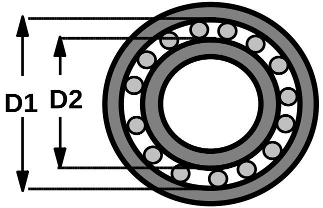


Use Limits : Load, Speed



Rolling Element Bearings

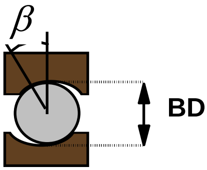
Bearing Frequencies



$$PD = \frac{D1 + D2}{2}$$

***n* = number of balls**

***f_r* = rotation frequency**



BPFO = $$f_{outer}\ (Hz) = \frac{n}{2} f_r \left(1 - \frac{BD}{PD}\cos\beta\right)$$

(Ball Pass Frequency of Outer race)

BPFI = $$f_{inner}\ (Hz) = \frac{n}{2} f_r \left(1 + \frac{BD}{PD}\cos\beta\right)$$

(Ball Pass Frequency of Inner race)

BSF = $$f_{ball}\ (Hz) = f_r \frac{PD}{BD}\left[1 - \left(\frac{BD}{PD}\cos\beta\right)^2\right]$$

(Ball Spin Frequency)

FTF = $$f_{cage}\ (Hz) = \frac{1}{2} f_r \left(1 - \frac{BD}{PD}\cos\beta\right)$$

(Fundamental Train Frequency)

Faults in Rolling Element Bearing

<table>
<tr><th colspan="2">Fault</th><th>Frequency</th><th>Time signal/ spectrum</th></tr>
<tr><td colspan="2">Outer race</td><td>BPFO, harmonics</td><td>Harmonics of BPFO</td></tr>
<tr><td colspan="2">Inner race</td><td>BPFI, harmonics</td><td>Initial fault : Harmonics
Progress : harmonics ± rotating frequency</td></tr>
<tr><td colspan="2">Ball/ roller</td><td>BSF or FTF, harmonics</td><td>Modulated natural frequency with FTF</td></tr>
<tr><td colspan="2">Unsuitable lubrication</td><td>Natural frequency, BPFI</td><td>Modulated natural frequency with BPFI</td></tr>
<tr><td rowspan="2">느슨함</td><td>Shaft & bearing</td><td rowspan="2">1X , harmonics
(2X, 3X, …)</td><td>3X or higher harmonics dominant</td></tr>
<tr><td>Housing & bearing</td><td>1X, 4X components dominant</td></tr>
<tr><td colspan="2">Excessive internal clearance</td><td>Natural frequency</td><td>Modulated natural frequency with RPS</td></tr>
</table>

Fault Frequency of Rolling Element Bearing (KOWACO)

880rpm
(8P)

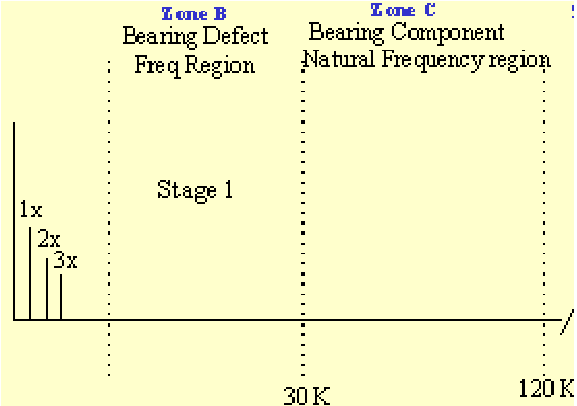
Wondong, Isacheon Pumping Stations

Point	Part. No	MFG.	BPFO	BPFI	FTF	BSF	No. of Ball
Pump DE	NU324	SKF	77.90	112.77	77.53	5.99	12
		FAG	83.86	121.44	77.44	5.99	13
Pump NDE	6324	SKF	45.92	71.41	64.34	5.74	8
		FAG	45.67	71.28	63.01	5.71	8
Motor DE	NU326	SKF	71.33	104.67	74.63	5.94	13
		FAG	83.86	121.44	77.44	5.99	14
Motor NDE	6330	SKF	52.18	80.08	67.23	5.80	9
		FAG	52.62	79.38	69.39	5.85	9
Pump DE	NU320	SKF	78.39	112.28	79.89	6.03	13
		FAG	78.50	111.76	80.61	6.04	13
Pump NDE	6320	SKF	45.07	72.27	59.87	5.63	8
		FAG	52.27	80.08	67.41	5.81	9
Motor DE/NDE	6326	SKF	45.95	71.39	64.46	5.74	8
		FAG	45.94	71.28	64.42	5.74	8

4 Failure Phases

Phase 1 :

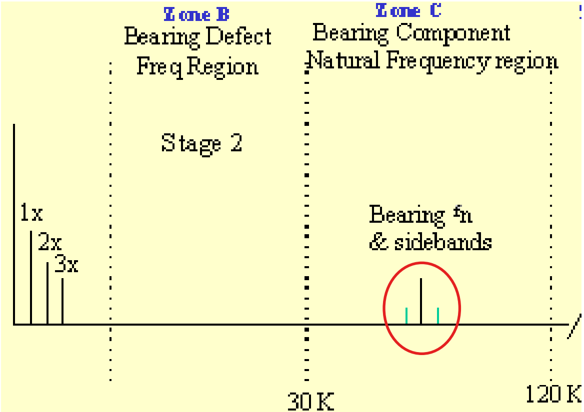
- **Earliest indications of bearing problems appear in ultrasonic frequencies ranging from approximately 20 ~ 60kHz**
- **Appear operation frequency and lower harmonics (2x, 3x)**



4 Failure Phases

Phase 2 :

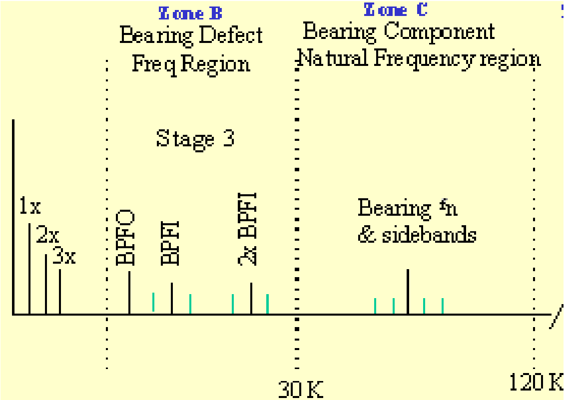
- **Slight bearing defects begin to "ring" bearing component natural frequencies (fn) which predominantly occur in the 30K ~ 120K CPM range.**
- **Sideband frequencies appear above and below natural frequency peak at end of phase 2**



4 Failure Phases

Phase 3 :

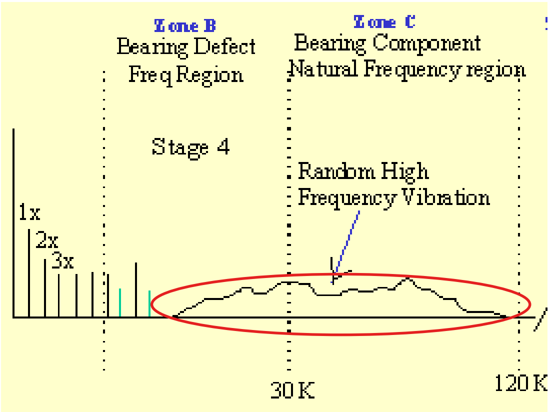
- **Bearing defect frequencies** and **harmonics** appear when wear progresses.
- **More defect frequency harmonics** appear and **a number of sidebands** grow, both around these and around bearing natural frequencies.
- Wear is now usually visible and may extend throughout periphery of bearing, particularly when well formed sidebands accompany any bearing defect frequency harmonics, replace the bearings now.



4 Failure Phases

Phase 4 :

- Towards the end, the amplitude of the 1x RPM is even effected.
- It grows, and normally causes growth of **many running speed harmonics**.
- Discrete bearing defect and component natural frequencies actually begin to "disappear" and are replaced by **random, broadband high frequency** "**noise floor**".
- In addition, amplitudes of both high frequency noise floor may in fact decrease

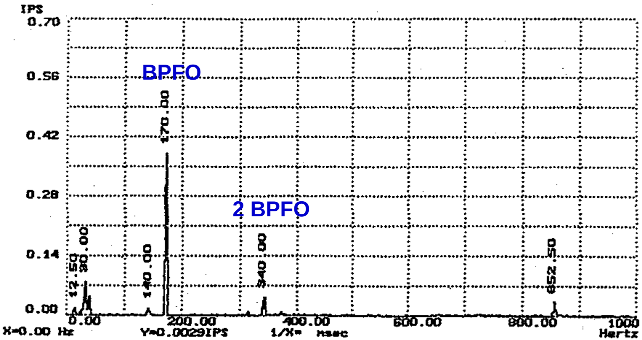


Case History : Outer Race Defects

- **Specification** : Roller Bearing(NU319), N = 29.6Hz, Z = 14, BD = 26mm, PD = 147.5mm, $\beta = 0^{o}$
- **Fault frequency :**

  BPFO = 29.6(14/2)(1- 1.024/5.807 × 1) = 170.67 Hz, FTF = 12.5Hz

- **Frequency analysis**
- **12.5Hz(FTF) : Looseness**
- **30Hz(N) : Unbalance**
- **170Hz(BPFO) : Outer race**
- **140Hz = 170 - 30: Sidebands**
  (운전속도 차), 축의 운동을 허용할 정도로 결함이 큼을 표시
- **340Hz : 2nd BPFO**
- **852.5Hz : 5th BPFO**

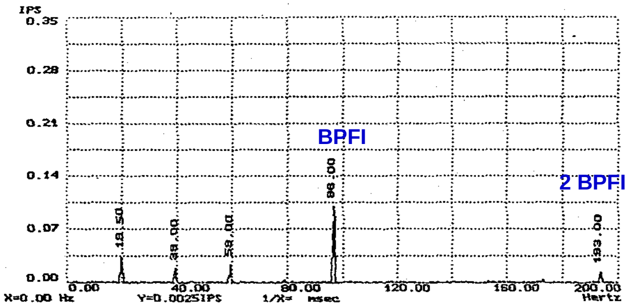


Outer race defect of roller bearing (NU319) for electric motor

Case History : Inner Race Defects

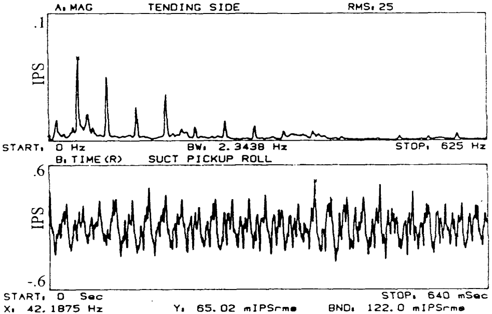
- **Specification** : Ball bearing (#6313), N = 19.6Hz, Z = 8, BD = 23.8mm, PD = 102.5mm
- **Fault frequency** : BPFI = 19.6(8/2) (1 + 23.8/102.5 × 1) = 96.9Hz

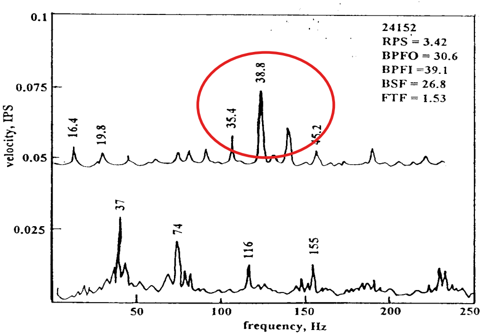
- **Frequency analysis**
- **19.5Hz : 1X**
- **39Hz, 59Hz : Harmonics, Looseness symptom**
- **96Hz : BPFI,** 변조(측대역성분)되지않음. 결함이 미소함을 표시
- **193Hz : 2nd BPFI**



Inner race fault for ball bearing

Case History : Inner Race Defects





Inner race fault of ball bearing

1) **BPFI : 37Hz**

2) **Harmonics : 74 Hz, 116 Hz, 155 Hz**

얇은 파편(shallow flaking)이 내륜에 발생

Spectrum after 2 weeks

1) 베어링상태 악화에 따라 측대역성분 발생

2) **Sideband : BPFI ± RPS**

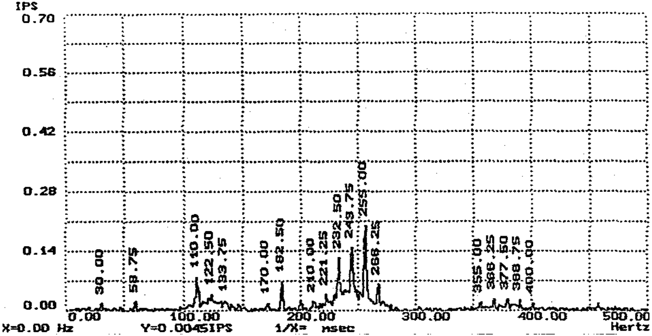
Case History : Ball Defects

• **2배 볼 자전주파수(2BSF)** : 구름요소(볼, 롤러)에 결함 시, 구름요소가 1회전 당 2개의 레이스(내, 외륜)에 충격을 가하며 회전할 때 발생. 접촉면을 통과할 경우이고, 볼의 자전방향이 일정하지 않으므로 측정 불가능한 경우도 있음.

• **기본열주파수(FTF)** : 케이지를 타격하거나 긁는 경우 발생. 독립된 주파수로 발생하지 않고, 다른 주파수를 변조. 이 성분이 크면, 여러 개의 구름요소에 결함을 표시

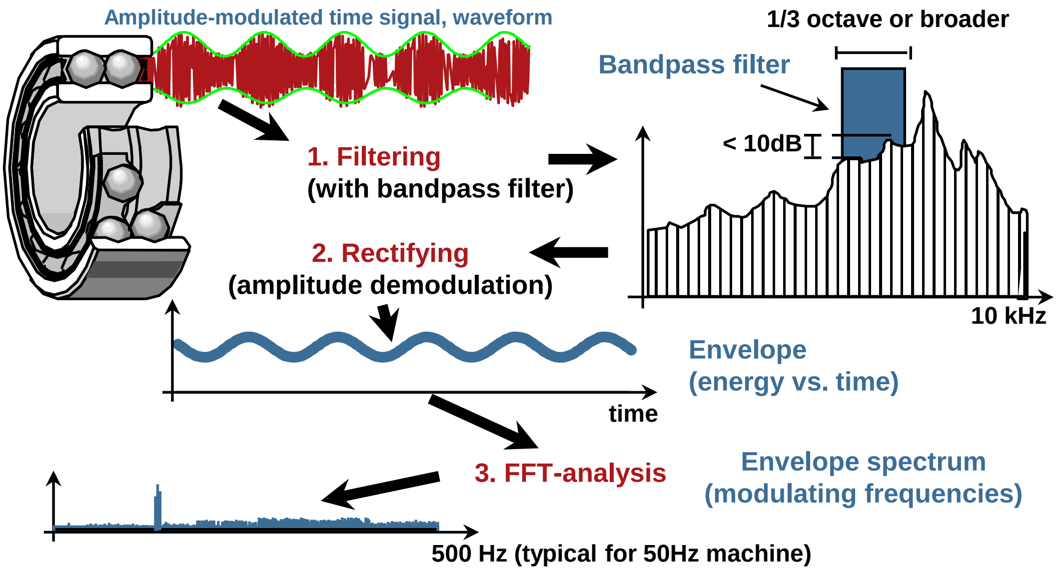
Frequency analysis

- **11.4Hz : FTF**
- **243Hz : Natural freq.**
- 고유진동수 영역에서 FTF로 변조된 주파수(210, 221.25, 232.5, 255, 266.25 Hz) 발생,
- 이에 따라 넓은 범위의 노이즈 생성



Vibration spectrum with 3 ball faults

Selective Envelope Detection (SED)

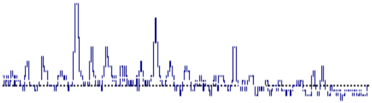


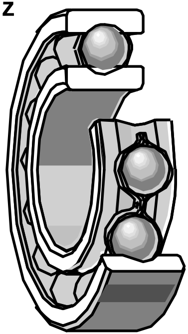
Selective Envelope Detection

Effective tool for detection and analysis

- Rolling element bearing faults
- Repeated shock wave
- Modulated random noise

- **Filtered Amplitude demodulated FFT analysis**
- **Envelope filter ranges in 1/3 octave bands from 709Hz to 44.7kHz**
- **10Hz - 20kHz of FFT display span**
- **Dynamic range ~90dB**
- **Tracking & gear exchange triggering**
- **Averaging 1 - 1000 (spectrum or enhanced)**





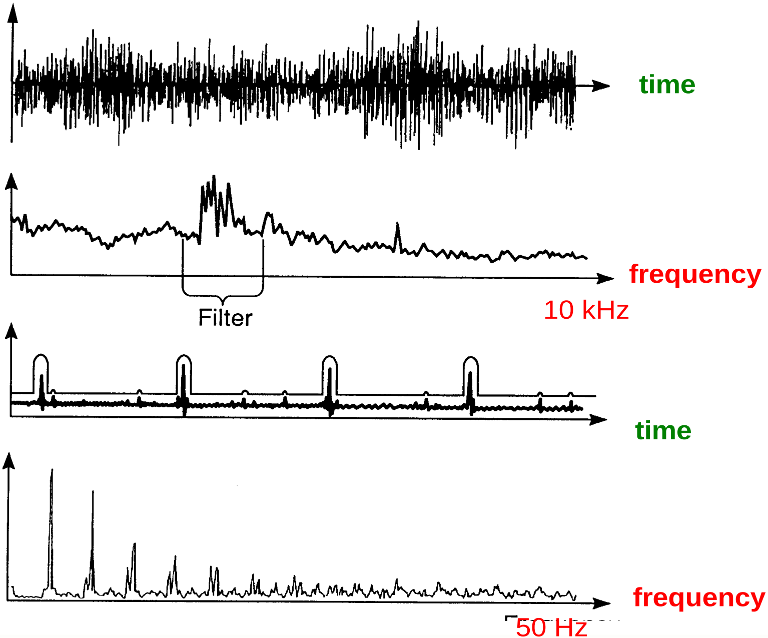
Envelope Analysis

Vibration
time
signal

Spectrum

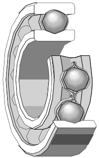
Filtered
time singal

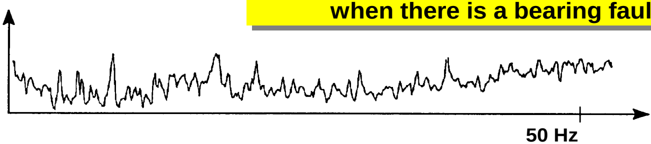
Envelope
Spectrum



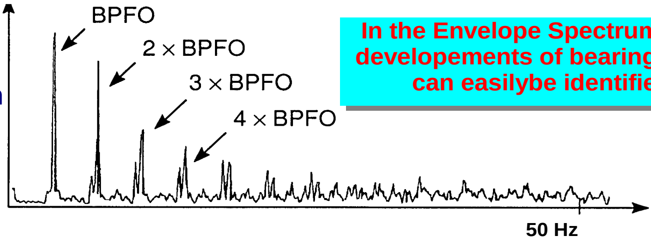
Bearing defects are easily seen in Envelope spectrum

In normal spectrum the bearing frequencies are not always visible when there is a bearing fault





Envelope Spectrum



In the Envelope Spectrum early developements of bearing faults can easilybe identified

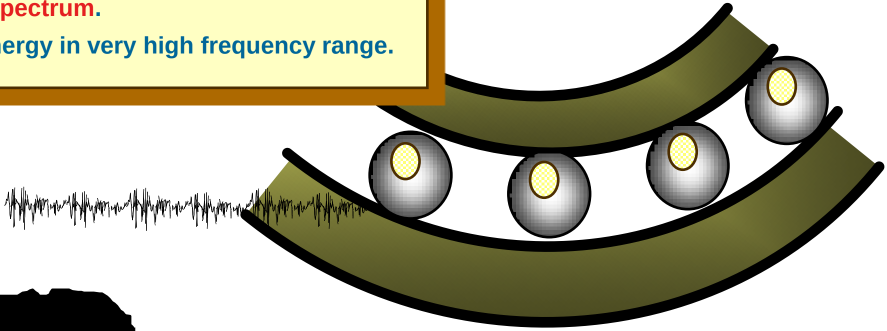
Envelope spectrum with no fault show no peaks !

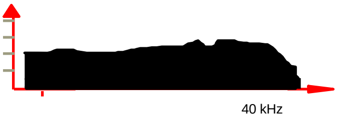
Random Noise

❖ When a rolling element bearing is rotating random noise is emitted caused by the **metal contact between the rollers and the bearing**.

❖ The random noise:

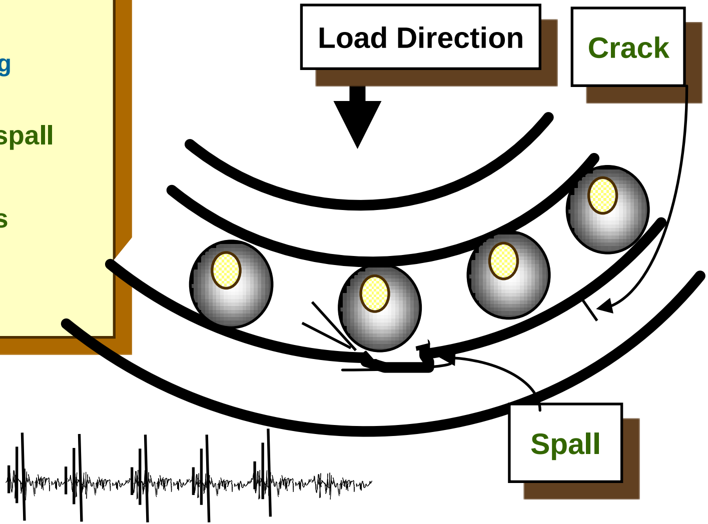
- has a **flat spectrum**.
- contains energy in very high frequency range.

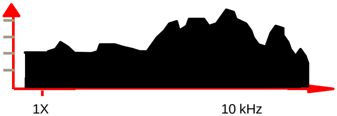




Beginning Wear

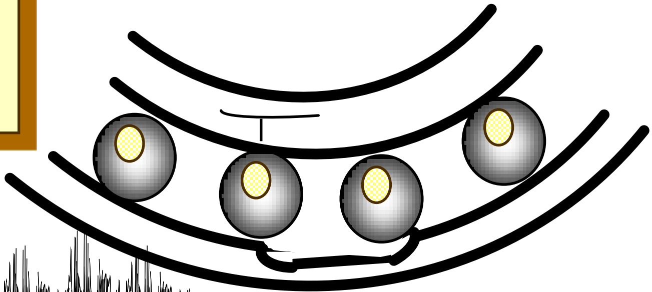
- ❖ The maximum metal stress of a rolling element bearing is
  - In the load zone of outer race
  - Few millimeters below the bearing surface.
- ❖ Most bearing wear starts as a spall or crack.
- ❖ The crack will produce Impacts
  - Energy in high frequencies
  - Exciting of bearing resonances.

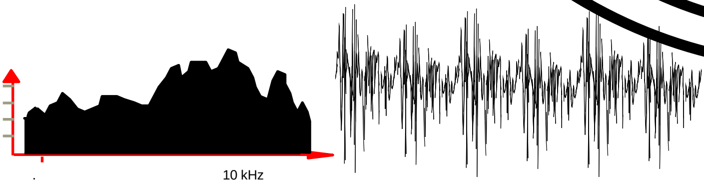




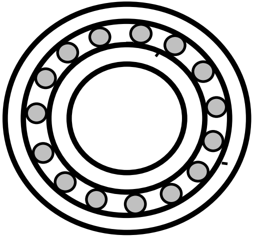
Progressing Wear

- As the wear progresses:
- Defects tend to smooth out
- The signal is not so impactive
- The random noise of the good bearing becomes modulated
- As the defect becomes deeper, the balls will jump and erode the inner race.



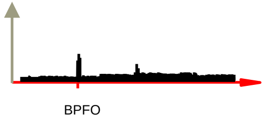


Bearing Faults



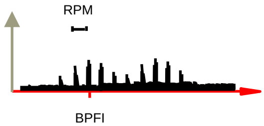
1. Outer Race Faults

- Lead Time Month's
- Ball Pass Frequency Outer Race (BPFO) and Harmonics



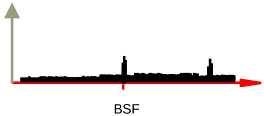
2. Inner Race Faults

- Lead Time Days - Weeks
- Ball Pass Frequency Inner Race (BPFI) with sidebands of rotational speed

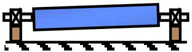


3. Ball Defects

- Requires Immediate action
- Ball spin frequency BSF with harmonics.
- Often in combinations with above with various harmonics.

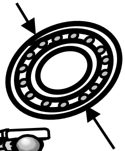


Mounting Rotor and Lubrication Defects



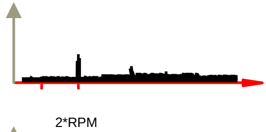
Rotor Misalignment
Rotor Unbalance
Force Revolution around outer race

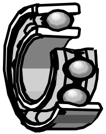
1×RPM



Radial Tension of Bearing

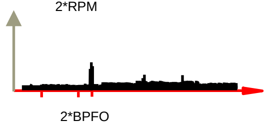
2×RPM

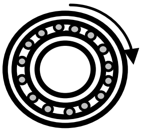




Misalignment of outer Race

2×BPFO



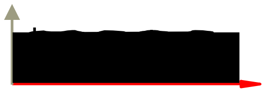


Slip of Race in the Mounting Seat

Harmonics of RPM

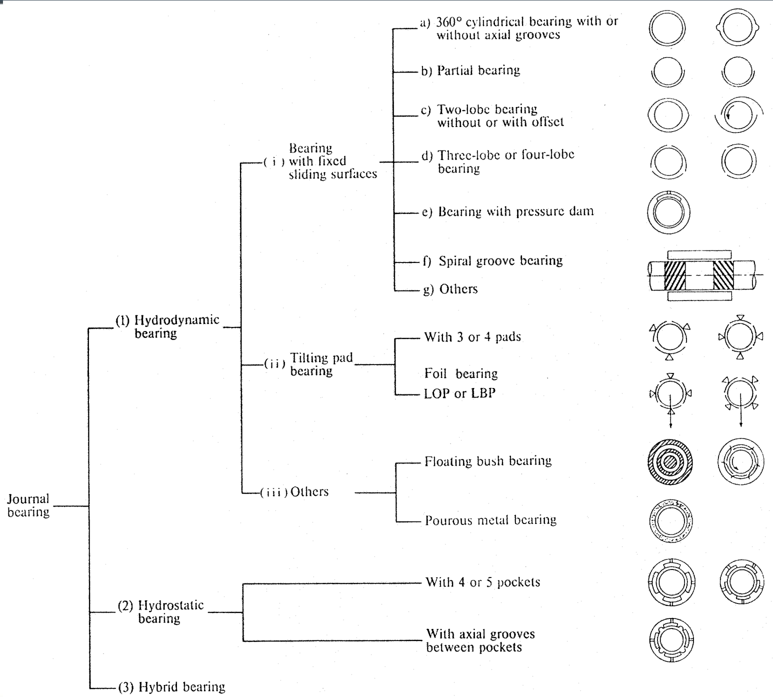
Lubrication Defect

Increase of Background level



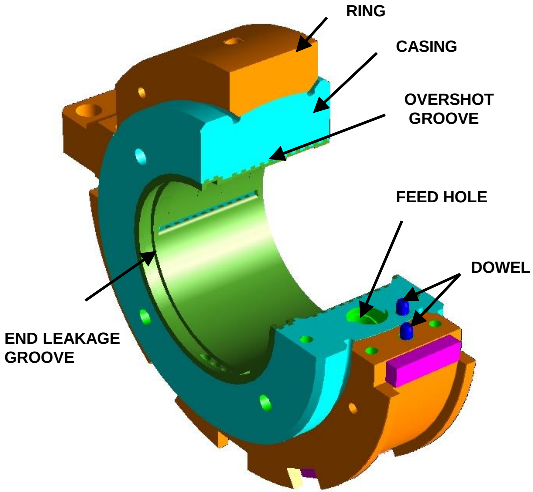
Fluid Film Bearings

Types of Journal Bearings



Elliptical Journal Bearing

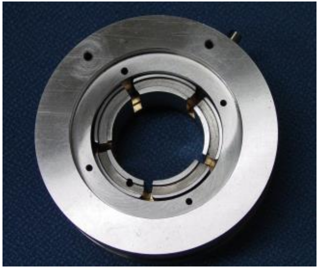
High load carrying capacity, simple, cheap

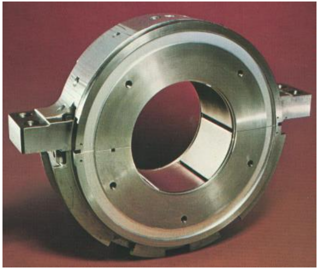


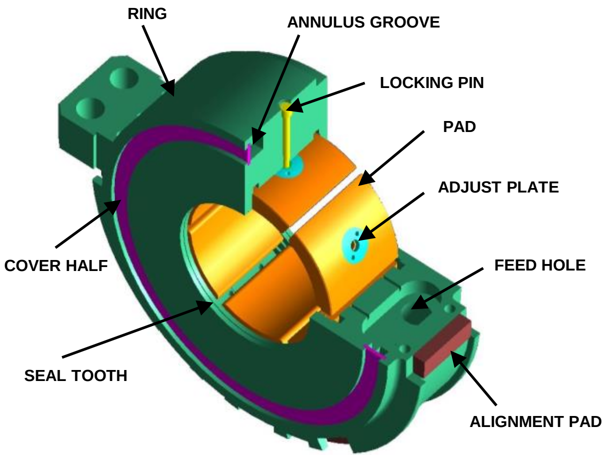
자료제공 : ㈜터보링크

Tilting Pad Journal Bearing

High stability, self-aligning, complex, expensive

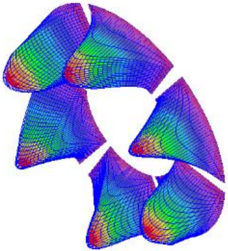


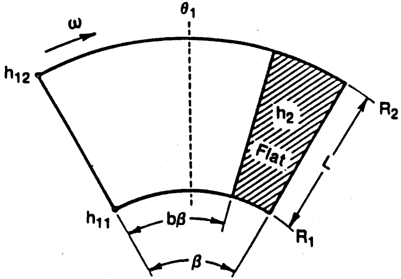


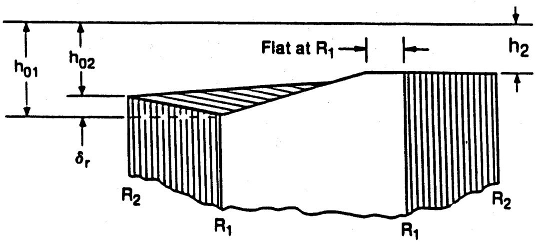


자료제공 : ㈜터보링크

Taper Land Thrust Bearing





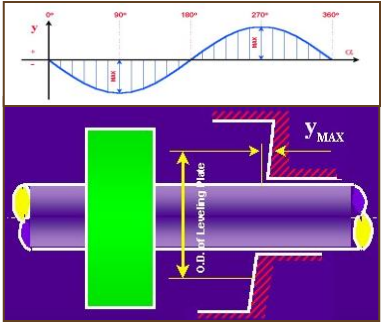


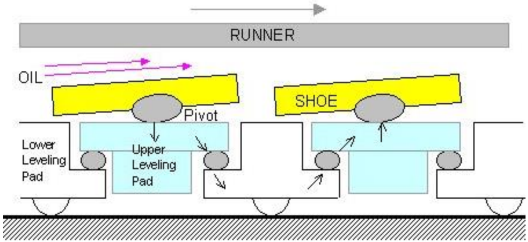
THRUST BEARING

Pivot shoe type self-equalizing thrust bearing

Self-equalizing:

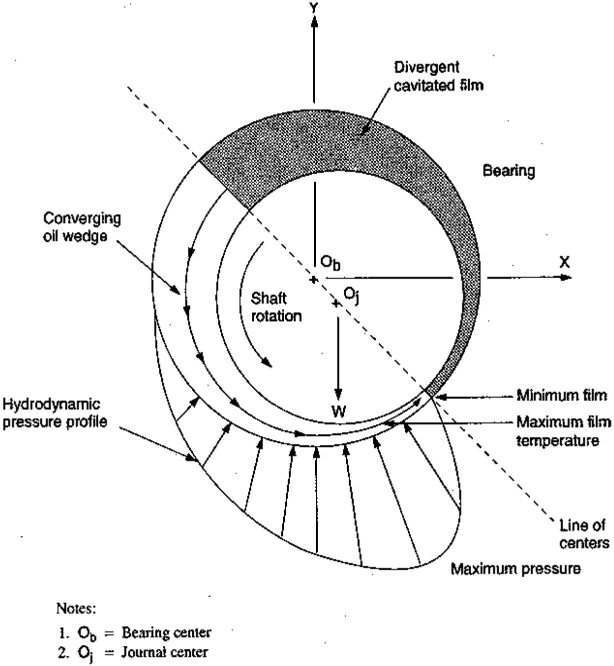
Misalignment 가 있더라도 leveling pad에 거의 모든 패드의 하중이 거의 일정하게 작용되도록 함





자료제공 : ㈜터보링크

Principle of Lubrication

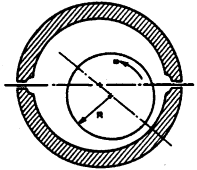


Hydraulic Pressure
- Shaft rotation (velocity)
- Oil suction (shearing force)
- Wedge effect (eccentricity)

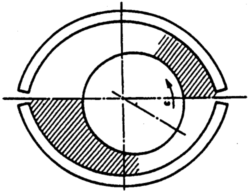
Important Design Variables
- Size, rotating speed
- Clearance, oil viscosity
- Load, shape etc.

동압: 점성유체가 채워져 있는 두 평판의 상대 운동에 의해 스스로 발생되는 압력

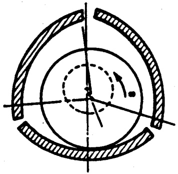
Common Hydrodynamic Journal Bearings



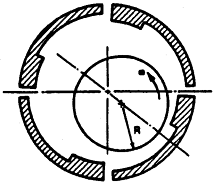
Circular



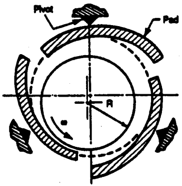
Elliptical



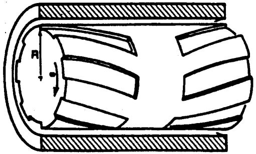
3-Lobe



Step



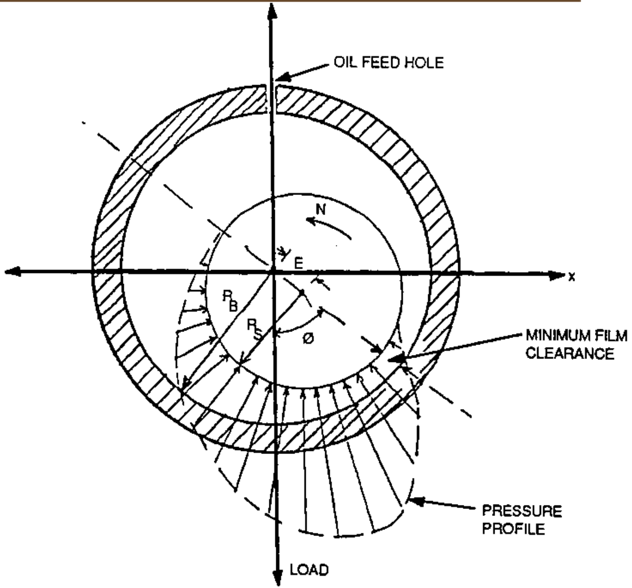
Tilting Pad



Herringbone

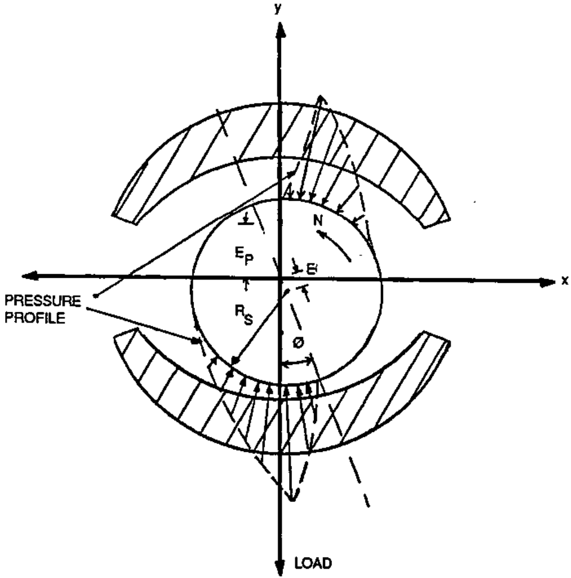
Principle of Lubrication

Plain (cylindrical) journal bearing

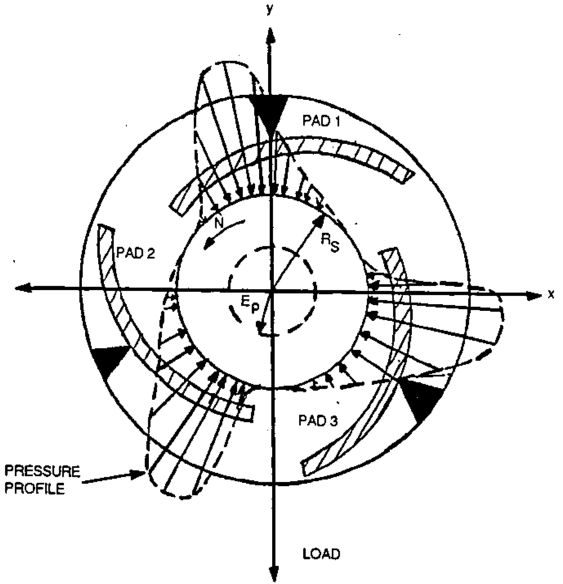


Principle of Lubrication

Elliptical journal bearing



Three-pad tilting pad journal bearing



Theoretical Analysis

❖ Performance Analysis of Journal Bearing

- **Static characteristics analysis**
  - Distribution of oil film pressure
  - Distribution of oil film thickness
  - Temperature distribution
  - Load capacity
  - Attitude angle
  - Friction loss & temperature rise
  - Minimum required oil flow rate

- **Dynamic characteristics analysis**
  - Stiffness and damping coefficient
  - Critical mass, threshold speed (stability criterion)

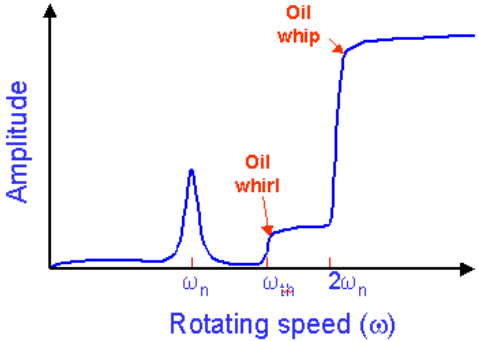
Instability

❖ Instability phenomena

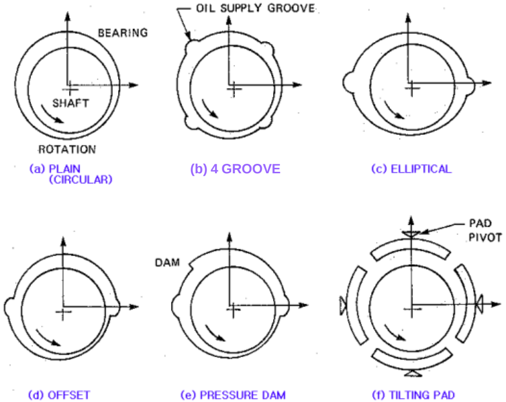
- Self-excited vibration due to stiffness and damping coefficient of oil film
- Oil whirl or oil whip phenomena
- Oil whip: resonance phenomena of system natural frequency & oil whirl frequency
- Stability characteristics will be changed bearing geometry, operating condition

❖ Remedial action

- Increase unit load
- Decrease oil viscosity
- Use tilting pad bearing
- Tilting pad bearing is best choice, stable always
- Circular → Pressure dam → Elliptical → 3-lobe → Tilting pad type



Effects of Bearing Geometry on Stability

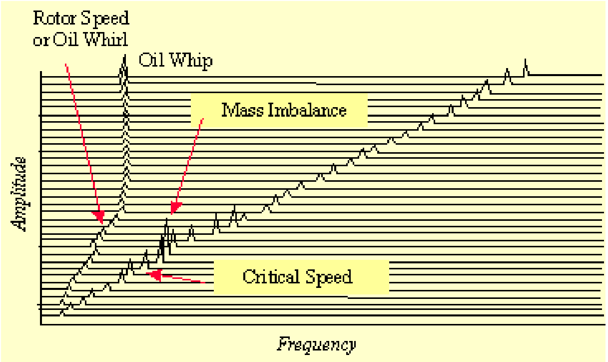


- 2-groove Circular
- 3- and 4-groove Circular
- Step Geometry
- Elliptical
- 3 - Lobe
- Tilting Pad

Order of Increasing Stability

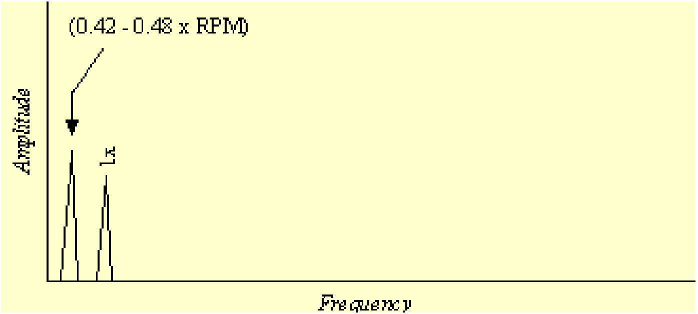
Oil Whip Instability

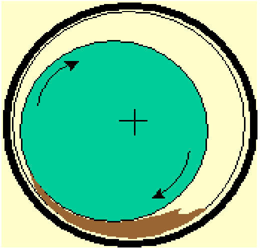
- A spectral map showing oil whirl becoming oil whip Instability as shaft speed reaches twice critical.
- Oil whip may occur if a machine is operated at or above 2 x rotor critical frequency.
- When the rotor is brought up to twice critical speed, whirl will be very close to rotor critical and may cause excessive vibration that the oil film may no longer be capable of supporting.
- Whirl speed will actually "lock onto" rotor critical and this peak will not pass through it even if the machine is brought up to higher and higher speeds.



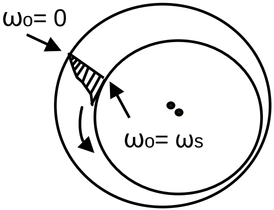
Oil Whirl Instability

- Oil whirl instability occurs at 0.42 ~ 0.48 × RPM and is often quite severe.
- Considered excessive when amplitude exceeds 50% of bearing clearances.
- Oil whirl is an oil film excited vibration where deviations in normal operating conditions (attitude angle and eccentricity ratio) cause oil wedge to "push" the shaft around within the bearing.
- Destabilizing force in the direction of rotation results in a whirl (or precession).
- Whirl is unstable since it increases centrifugal forces which increase whirl forces.
- Can cause oil to no longer support the shaft, or can become unstable when whirl frequency coincides with a rotor natural frequency.
- Changes in oil viscosity, lube pressure and external pre-loads can affect oil whirl.





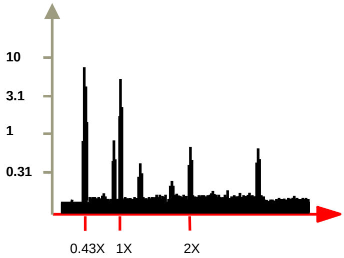
Journal Bearing Faults

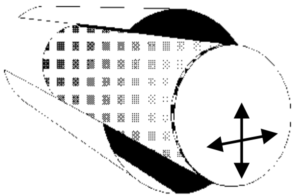


$\overline{\omega}_o \sim 0.3 - 0.5\ \omega_s$

Oil Instability

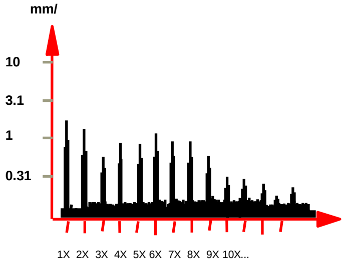
- Normally 42%~ 47% of running speed
- May appear from 0.3~0.7X in some occasions
- Non synchronous





Wear
Clearance Problems

- Harmonic series of rotational speed



Failure Causes

Design

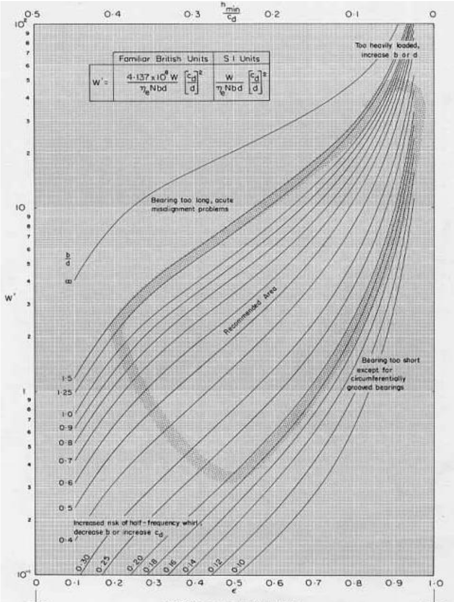
- Improper type
- Excessive load
- Light load
- Excessive clearance
- Small clearance

Operation

- Misunderstand operational manual
- Improper Flushing
- 이물질 혼입
- Frequent start & stop
- Lubrication breakdown

Manufacturing

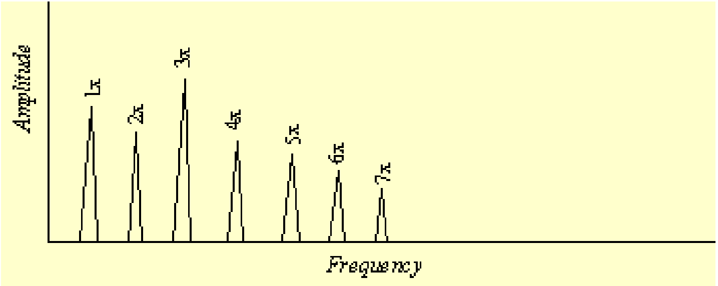
- Improper material
- Poor bonding
- Under/over cutting
- Misalignment
- Unbalance



Load capacity diagram
for plain journal bearings

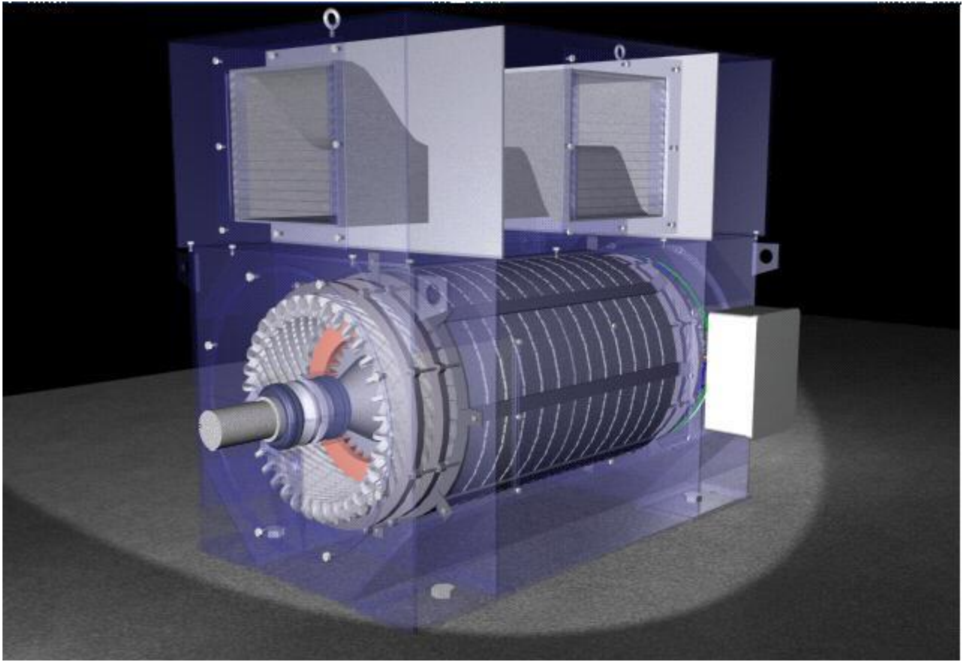
Wear / Clearance Problems

- Latter stages of sleeve bearing wear are normally evidenced by the presence of whole series of running speed harmonics (up to 10 or 20).
- Wiped sleeve bearings often allow high vertical amplitudes compared to horizontal.
- Sleeve bearings with excessive clearance may allow a minor unbalance and/or misalignment to cause high vibration which would be much lower if bearing clearances were to specification.

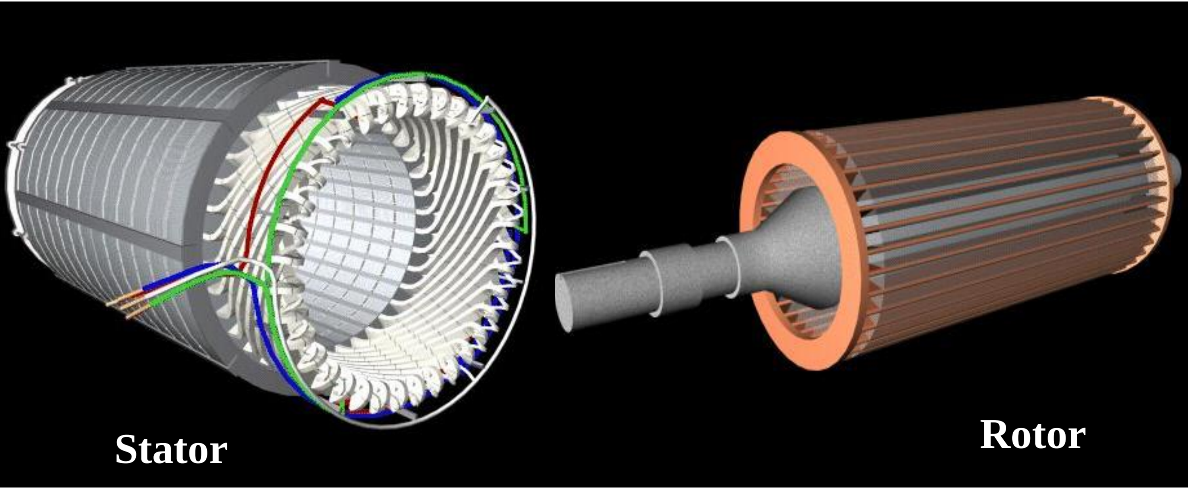


Electric Motors

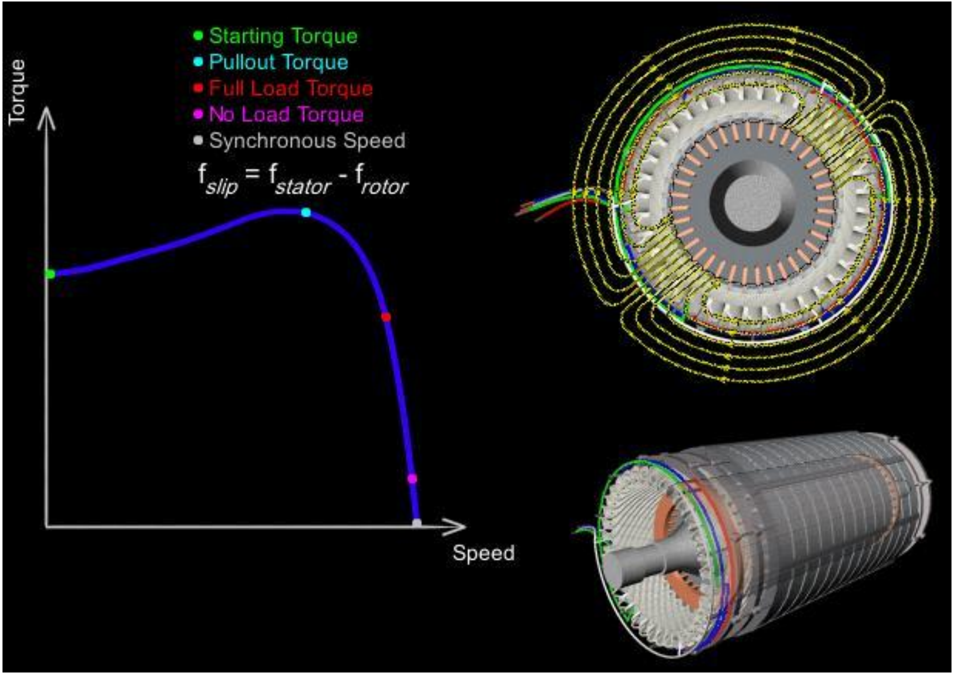
Induction Motors



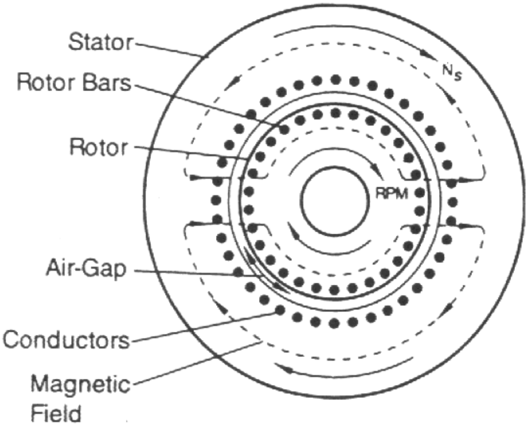
Rotor and Stator



Speed vs. Torque



Characteristic Frequency



$N_s = \frac{120 F_L}{P}$ = SYNCHRON. SPEED

$F_s = N_s$ - RPM = SLIP FREQ.

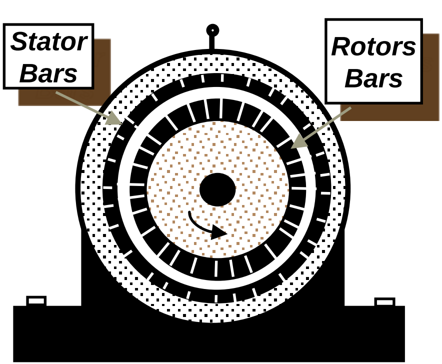
$F_p = (F_s)(P)$ = POLE PASS FREQ.

RBPF = # ROTOR BARS X RPM

WHERE:

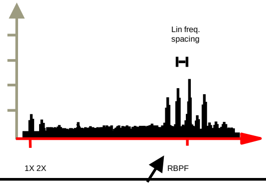
F_L = ELECTRICAL LINE FREQUENCY
RPM = ROTOR SPEED
N_s = SYNCHRONOUS SPEED
F_s = SLIP FREQUENCY (N_s - RPM)
F_p = POLE PASS FREQUENCY
P = # POLES
RBPF = ROTOR BAR PASS FREQUENCY

Electric Motor : Cracked Rotor Bars



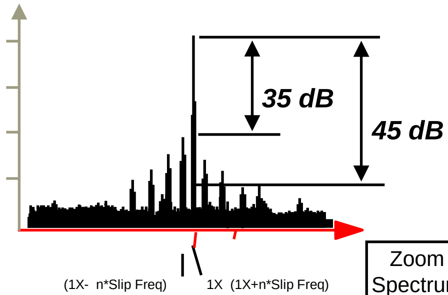
Broken Rotor Bars
Cracked Rotor Bar
Loose Rotor Bar
Shorted Rotor Laminations
Poor End Ring Joints

- Side bands of ***Slip Freq*** around ***1X, 2X 3X etc.***
  < - 35 dB = Serious
  > - 45 dB = OK.



Loose Rotor Bars may also cause Sidebands of Line frequency around Rotor bar passing frequency and 2*RBPF

Pole Pass Freq. = Slip Freq.* No. of Poles
Slip Freq. = Synch Speed - RPM
Rotor Bar Freq. = No. of rotor Bars * RPM



Zoom Spectrum

Analysis Method for Electric Faults

- 전기적인 원인에 의한 결함이 의심되면, 전기적인 상태를 평가하기 위해 전부하(full load) 또는 그 부근의 상태에서 조사가 필요.
- 이는 특히 전자기력이 고정자 전류의 제곱에 비례하여 변화하기 때문.
- 종종 전기적인 문제는 단독시험(solo test)이나 심지어 무부하(no load) 상태로 운전하여도 증상을 나타내는 진동신호가 발생하지 않는 경우가 있음.
- 이 경우는 100% 부하를 받을 때 명확한 증상이 나타남
- 대부분의 전기적인 문제는 2X전원주파수(2F_L, 120Hz 또는 100Hz)에서 정상상태 보다 높은 진동진폭이 발생하고, 이를 이용하여 감지
- 불평형, 정렬불량 등의 기계적인 문제가 회전자와 고정자 사이의 공극 변화와 같은 전기적인 문제를 야기시킴. 따라서 기계적인 문제를 먼저 검토하고, 그 원인을 제거한 후 전기적인 문제를 검토하는 것이 바람직.
- 결함을 분석할 때에는 전동기의 전류분석을 함께 실시하는 것이 바람직. 전동기 내의 자기장(magnetic field)은 전자기력을 일으키는 자속(flux)을 발생.
- 이 힘은 기계적인 가진력과 함께 모두 베어링에 의해 지지됨.
- 양호한 주파수 분해능과 확대 스펙트럼(zoom spectrum) 분석이 중요. 이는 기계적인 문제(운전주파수, 조화성분)와 전기적인 문제(전원주파수, 조화성분)의 분리에 필요

Fault Type

◆ Mechanical Fault

Elements	Faults
Bearing	• Rolling element bearing defect (ball, Inner & outer race, cage) • Journal bearing defect (oil whip/whirl, wear etc.)
Shaft	• Mass unbalance, bent shaft, looseness, rubbing, resonance
Coupling	• Misalignment (parallel, angular)

◆ Electrical Fault

Elements	Faults
Air-gap	• Air-gap unbalance (stator eccentricity, rotor eccentricity)
Rotor, end ring	• Rotor bar breakage / crack • Rotor bar looseness / open • Rotor lamination short • Rotor bar thermal bow due to local overheating • End ring breakage / crack
Stator	• Flexible stator • Stator lamination short • Stator lamination looseness

Vibration in Electric Motors

Fault	Frequency	Spectrum	Action
Air-gap variation	120Hz	120Hz 성분, 운전속도의 배수성분과 120Hz와의 beat	- 프레임의 변형 제거, - 아마추어와 고정자의 중심 조정
Stator short	120Hz harmonics	120Hz, harmonics	- 고정자 교체
Flexible stator	120Hz	2x와 120Hz와의 beat	- 고정자 강도를 키움
Rotor bar breakage	1x	1x와 sidebands (slip freq. × No. of pole)	- 파손된 바의 교체
Rotor eccentricity	1x	120Hz와 fp의 측대역 성분 1x, 2x 와 120Hz와의 beat	- 공극 변동이 발생할 수 있음
Magnetic center variation	1x, 2x	Impact in axial direction	- 베어링 추력과 커플링 등에 의한 축-방향 제약조건을 제거

Air-gap Problems

Static eccentricity

- Stator core ovality
- Incorrect positioning of the rotor or stator

Dynamic eccentricity

- Bent shaft
- Mechanical resonance at C. S.
- Bearing wear

Characteristics

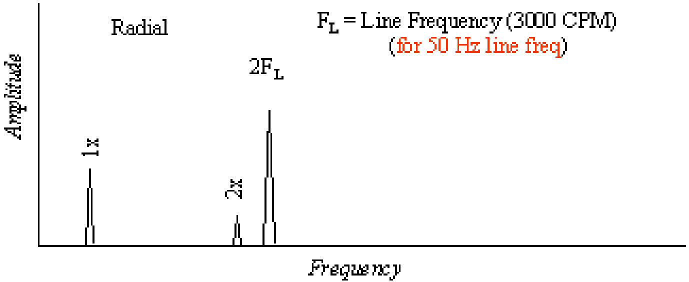
- 2 x line frequency ($2F_L$)
- Same symptom of stator fault ($2F_L$, $F_s \pm 2kF_L$)
- Different classification between these faults

Causes

- Unequal center line of stator and rotor

Stator Eccentricity, Shorted Laminations & Loose Iron

- Stator problems generate high vibration at 2x line frequency ($2F_L$).
- 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.



Eccentric Air-Gap (Variable Air-Gap)

- Eccentric Rotors produce a rotating variable air gap between rotor and stator which induces pulsating vibration (normally between ($2F_L$) and closest running speed harmonic).
- Often requires "zoom" spectrum to separate the ($2F_L$) and the running speed harmonic.
- Eccentric rotors generate ($2F_L$) surrounded by Pole Pass frequency sidebands (F_P) as well as F_P sidebands around running speed F_P appears itself at low frequency (**Pole Pass Frequency = Slip Frequency x # Poles**).
- Common values of F_P range from approximately 20 to 120 CPM (0.30 ~ 2.0 Hz)

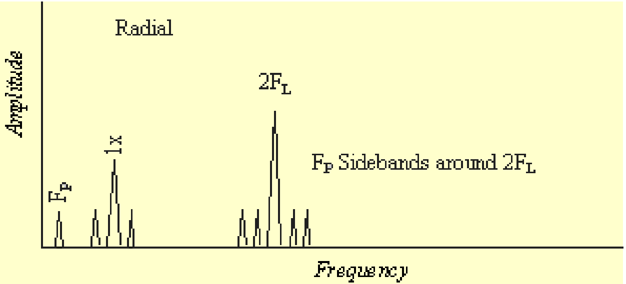
F_L = Electrical Line Frquency

N_S = Synch. Speed = $20F_L/P$

F_S = Slip Freq. = N_S - RPM

F_P = Pole Pass Freq. = F_S*P

P = Number of Poles



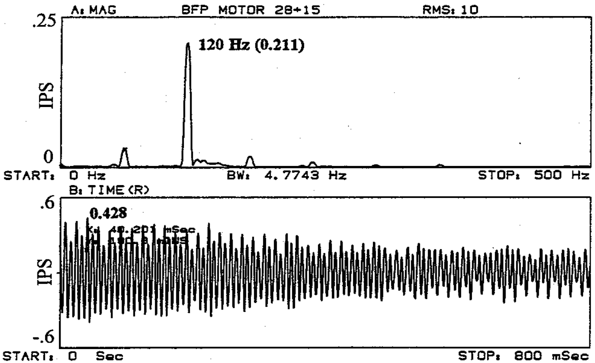
Case History : Air-gap Problem

◆ **Cause :**

- Motor unbalance, armature eccentricity, flexible stator

◆ **Symptom :**

- 2 times of line frequency (120Hz)



Vibration signal of induction motor (4,000 HP)

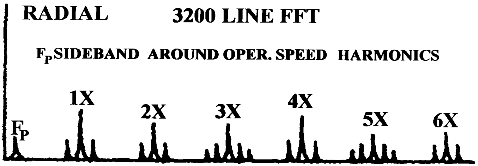
Rotor Problems

Causes :

- Broken/ cracked Rotor Bar
- Broken/ cracked end ring, bad coupling between rotor bar and end ring
- Rotor lamination short, loosed/ opened rotor bar
- Electric arcing between loosed rotor bar and end ring

Symptoms :

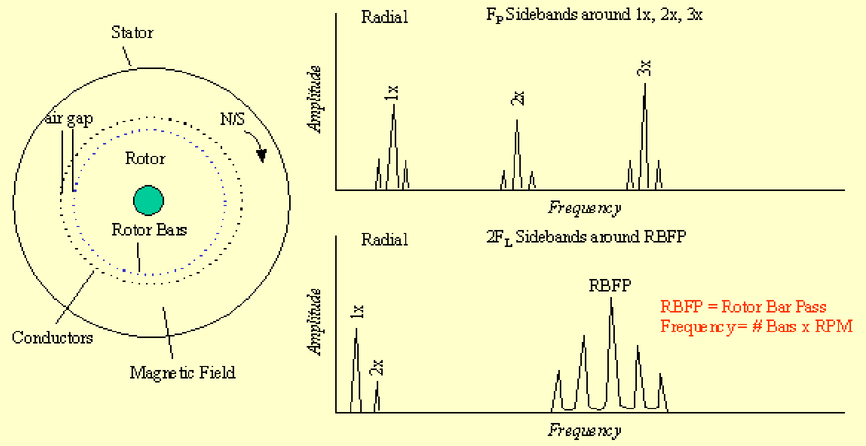
원인	증상
❖ 회전자 봉과 단락 링의 파손/ 크랙 ❖ 회전자 봉과 단락 링 사이의 불량 결합 ❖ 회전자 적층의 단락	• 운전속도(1X) 성분의 높은 진동과 • 극 통과주파수 (F_P)의 측대역 성분 발생
❖ 크랙이 발생한 회전자 봉	• 운전속도(1X)의 높은 진동과 극 통과주파수(F_P)의 측대역 성분 발생. 종종 조화성분(2X, 3X, 4X, 5X)의 주위에 F_P의 측대역 성분 발생
❖ 헐겁거나 개방된 회전자 봉	• 회전자 봉 통과주파수(RBPF)와 이의 조화성분 및 주위에 $2F_L$의 측대역 성분
❖ 회전자 봉과 End ring 사이의 전기적 아크	• $2F_L$과 2×RBPF 성분의 높은 레벨



Vibration spectrum

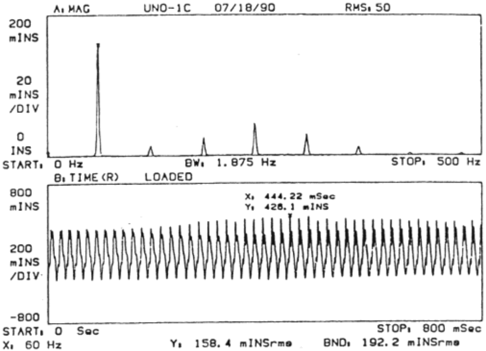
Rotor Bar Problems

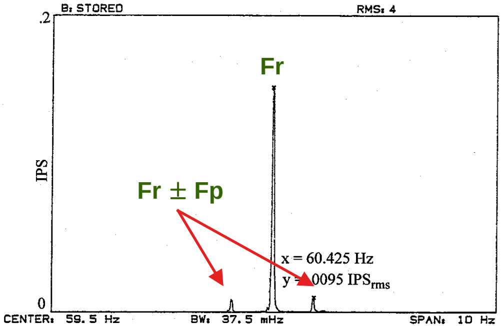
- Broken or cracked rotor bars or shorting rings, bad joints between rotor bars and shorting rings, or shorted rotor laminations will produce high 1x running speed vibration with pole pass frequency sidebands Fp.
- In addition, cracked rotor bars will often generate Fp sidebands around the 3rd, 4th and 5th running speed harmonics.
- Loose rotor bars are indicated by 2x line frequency ($2F_L$) 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.**



Case History 1 : Broken Rotor Bar

- Broken or loosed rotor bar is occurred when motor is connected with load
- 운전주파수 **Fr** 부근에 극 수와 슬립주파수를 곱한 극 통과주파수(pole passing frequency) **Fp**와 같은 간격의 **측대역(sideband) 성분 Fr ± Fp 발생**

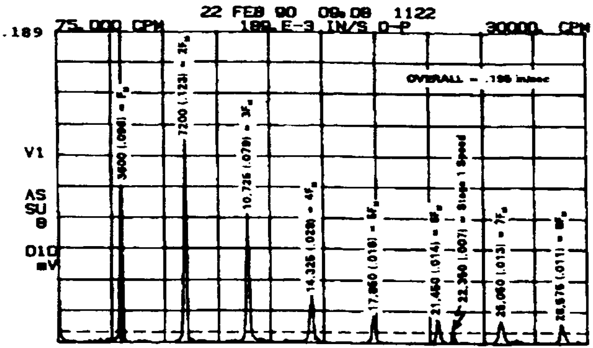




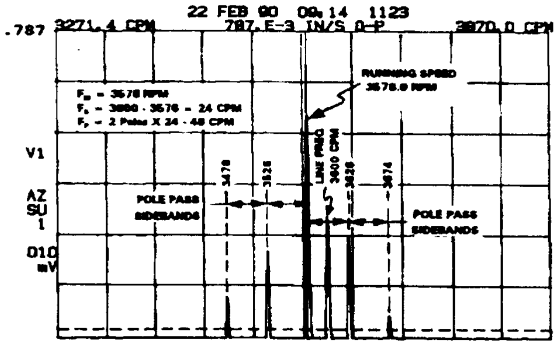
Vibration in broken rotor bar (2,000 HP)

Case History 2 : Broken Rotor Bar

- Symptom frequency for broken or cracked rotor bar and end ring, shorted rotor lamination : 1X ± Fp (2 pole motor : Fp = 2 Fs, 4 pole motor : Fp = 4 Fs)
- Broadband spectrum (Fig. a) : 1X, harmonics, symptom of mechanical looseness
- Zoomed spectrum (Fig. b) : 1X ± Fp, 2X ± Fp



a) Broadband spectrum

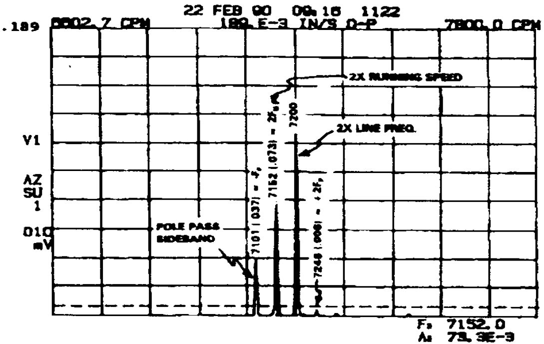


b) Zoomed spectrum(1X)

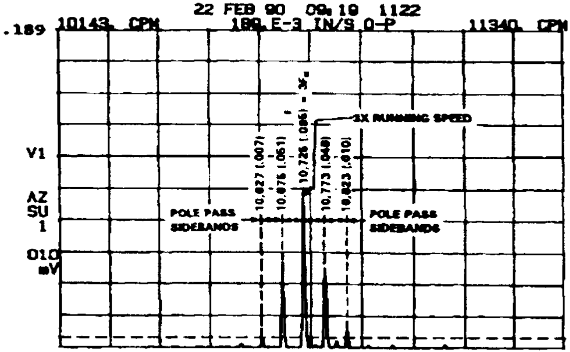
Vibration spectrum for rotor bar fault

Case History 2 : Broken Rotor Bar

- ◆ Zoomed spectrum (Fig. c - d) : 1X, 2X, 3X, 4X 등의 주변에 잘 형성된 PPF 성분의 측대역 성분 발생
- ◆ Pole Passing Frequency (PPF) : Fp = No. of poles (P) × slip frequency (Fs)
- ◆ Rotating speed : 1176 rpm, Fs = 24 cpm (0.4 Hz), Fp = 6 × 24 = 144 cpm (2.4 Hz)
- ◆ 4 cracked rotor bars. 고차 조화성분의 발생은 1개 이상의 봉에 결함이 발생함을 의미



c : 2X 확대 스펙트럼

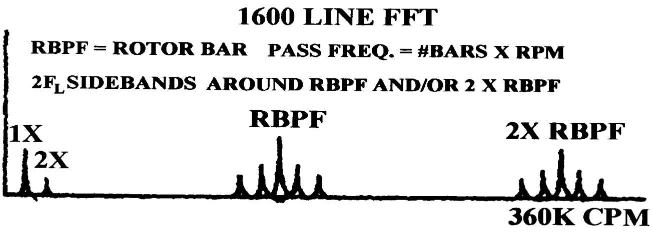


d : 3X 확대 스펙트럼

그림 4-11 회전자 봉 결함 진동 스펙트럼

Loose or Open Rotor Bar

- **Cause :** Looseness or open of rotor bar
- **Symptom Frequency :** 회전자 봉 통과 주파수(RBPF)의 매우 높은 주파수의 진동과 이의 조화성분들이 발생
  - Rotor Bar Passing Frequency (RBPF) = No. of rotor bar × RPM
  - RBPF, 2 × RBPF 또는 3 × RBPF에서 진폭이 대략 1.5 mm/s를 초과할 때 문제가 됨
  - RBPF와 이의 조화 성분 주위에는 정확하게 2배 전원주파수($2F_L$)의 측대역(sideband) 성분이 존재

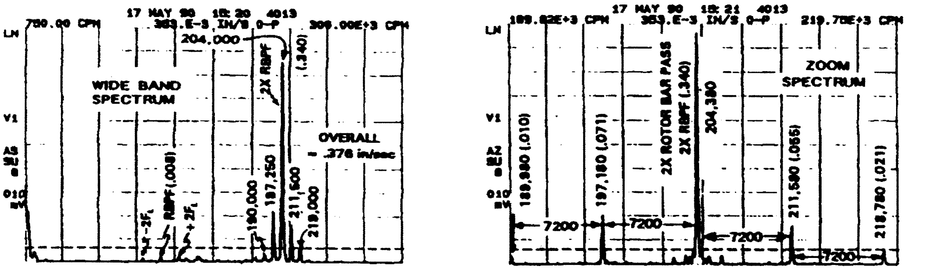


$RBPF \pm 2nF_L$

$2 \times RBPF \pm 2nF_L$

Case History : Opened Rotor Bar

- **Symptom frequency for loosed or opened rotor bar**
  - Rotor Bar Passing Frequency (RBPF), harmonics (2RBPF etc)
  - Sidebands : RBPF ± $2F_{L}$, 2RBPF ± $2F_{L}$
  - RBPF : F_{rp} = No. of rotor bar × Fr = 57 × 1,793 rpm = 102,201 cpm (1,703 Hz)
- **Zoomed spectrum (Fig. a, b)**
  - RBPF : 0.203 mm/s (0.008 in/s), very small amplitude
  - 2 × RBPF : 8.636 mm/s (42 times of RBPF), very large amplitude
  - 2 × RBPF ± $2F_{L}$ (7,200 cpm) : sidebands
- **Confirmed over two opened rotor bars by overhaul**



Vibration spectrum for fan motor

Stator Problems

◆ Detectable Stator problems by Vibration Analysis

- **Stator Eccentricity**
  - **Cause :** 연약 지반(soft foot), 뒤틀린 기초(warped base)
  - 회전자와 고정자 사이의 불균일한 정적 공극(stationary air-gap)의 미소한 차를 발생시키는 편심
- **Shorted Stator Lamination**
  - **Cause :** 고정자 적층의 절연문제 (insulation problem of stator lamination)
  - 고정자 자체를 뒤틀리게 할 수 있는 불균일하고 국부적인 열을 야기
  - 운전시간과 함께 크게 성장할 수 있는 thermal induced vibration을 발생
- **Loose Iron**
  - **Cause :** Weakness and looseness of stator supports

◆ Symptom frequency : $2F_L$

Vibration due to Stator Fault

◆ Characteristics

- 진동수는 전원 주파수의 2배 (2F_L)
- 전동기 전원을 차단하면, 이 진동성분은 일순간에 소멸
- 진동은 고정자 프레임이나 베어링등에 발생
- 극통과주파수(Pole Passing Frequency)의 측대역성분이 발생하지 않음
- 고정자 내에서 발생, 운전속도나 슬립주파수에 의해 변조되지 않기 때문
- 고정자 문제 파악의 중요한 지침

◆ Causes

- 일반적으로는 전동기의 기초나 공통 베드와 케이싱 사이의 볼트가 느슨해져 전동기의 공진주파수가 낮아지고, 2F_L에 10%이내로 접근하여 공진을 일으키는 경우가 많음
- 고정자권선의 각 상 사이(단상, 3상 전원)에 전기적 불평형이 있어도 전자 진동을 발생
- 철심이나 고정자 권선이 느슨해져 고정자 진동이 증대할 때는 더 큰 진동을 수반하므로 2 n F_L (n = 1, 2, 3, …) 성분도 발생

Vibration due to Stator Fault

◆ Discrimination Guideline for Normal/Abnormal

- **Peak value of $2F_L$ component (120Hz) :**
  - **New or reassembled induction motor (50 ~ 1,000HP) : < 1.25 mm/s**
  - **Operating motor (50 ~ 1,000 HP) : < 2.54 mm/s**
  - **Precision machine tool spindle : < 0.625 mm/s**

◆ Criterion for Trend Monitoring

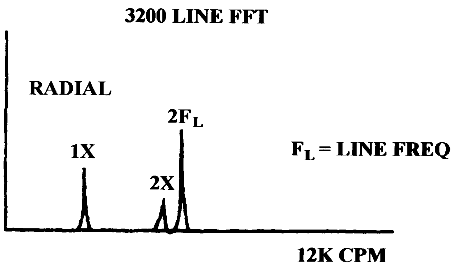
- 예지 정비 (상태감시기반 정비) 프로그램을 가지는 경우, **$2F_L$ 성분의 피크치가 2.54 mm/s 를 초과할 때는** 향후 조사를 위해 경향감시가 필요
- 피크치가 크게 증가하거나, 측대역 성분이 **$2F_L$**성분의 좌우에 나타나면, 집중감시가 필요
- 피크치의 크기가 **4.45 mm/s** 이하의 안정한 상태를 유지하면, 경향감시만 실시

◆ Allowable Air-gap Eccentricity

- **Induction motor 5%, synchronous motor 10%** 이내

Stator Eccentricity

- **Cause :** 연약 지반(soft foot)과 뒤틀린 기초(warped base) 는 편심 고정자를 발생시킴
- **Symptom frequency :** 고정자 문제는 전원주파수 2배수($2F_L$)에서 높은 진동을 발생
- 고정자 편심은 매우 지향성의 진동을 발생시키는 회전자와 고정자 사이의 불균일한 정지된 공극을 발생시킴



Vibration spectrum

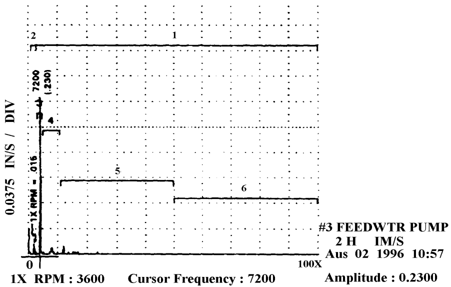
Case History : Stator Eccentricity

◆ **Analysis results of Broad band spectrum (Fig. a) :**

- 정기적인 상태감시정비 기간 중에 취득한 자료
- 회전속도(3,560 rpm) 성분 속도 진폭치 : 0.381 mm/s (0.015 in/s)
- $2F_L$ (7,200 cpm) 성분 피크치 : 5.842 mm/s (0.230 in/s)
- 한계치(영역 3)를 초과하는 과대한 진동 발생

◆ **Analysis results of zooming spectrum (Fig. b) :**

- 회전속도의 2배 성분 (7,173 cpm) 의 진폭 : 0.111mm/s (0.0044 in/s)
- $2F_L$ 성분 (7,200cpm)의 진폭 : 5.791mm/s (0.228 in/s), 가장 탁월 극 통과주파수 성분이 발생하지 않음



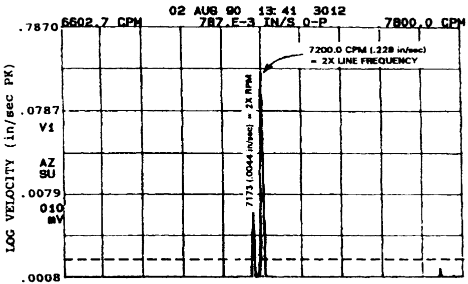


그림4-14 급수펌프 구동용 전동기의 고정자 편심 진동

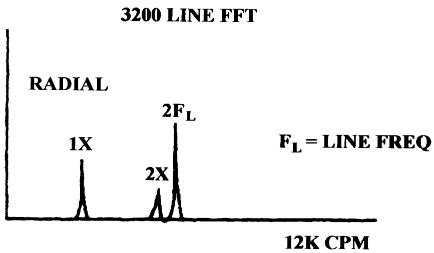
Shorted Stator Laminations

◆ **Causes :** poor core construction of stator

예) 큰 펀치 버어(heavy punction burr), 불량 적층 정렬, 불량 철심 판 절연(core plate insulation), 너무 무겁거나 혹은 너무 가벼운 철심 압력, 마찰 혹은 철심에 대한 외부 금속 물질 같은 물리적 손상 등

◆ **Symptom frequency : 2X (rotor), 2F_L (stator)**

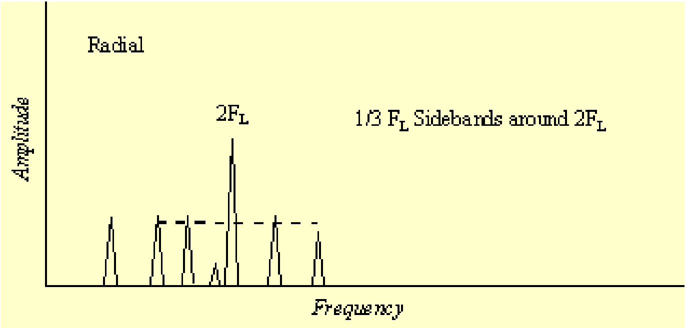
- 고정자와 회전자 모두 진동의 두드러진 증가는 철심 단락(core shorting)의 존재를 나타냄
- 단락된 고정자 적층은 고정자 자체를 뒤틀리게 할 수 있는 불균일하고, 국부적인 열을 야기시킬 수 있고, 운전시간과 함께 중대하게 성장할 수 있는 열 여기진동(thermally-induced vibration)을 발생
- 불행히도 진동 pick-up에 의해 일단 감지되면 단락은 급속도로 진전되므로, 이 때는 너무 늦음
- 보다 빠른 지시계로는 매우 낮은 크기의 단락된 철심 전류를 감지기(detector)로 이용



Vibration spectrum

Phasing Problems

- Phasing problems due to **loose or broken connectors** can cause excessive vibration at 2 x line frequency ($2F_L$) which will have sidebands around it at 1/3rd line frequency (1/3 F_L).
- Levels at $2F_L$ can exceed 25 mm/s if left uncorrected.
- This is particularly a problem if the defective connector is only sporadically making contact and periodically not.



Recommended Maximum Measurement Frequency

◆ Fault frequency identification

- In low frequency region :
  - F_{max} = 200 Hz (12,000 cpm), 3200 FFT line, 2 Average
  - $2F_L$ 성분과 전동기 운전속도 및 이의 조화 성분의 참 진폭을 분리 가능
- In high frequency region：
  - Over 4 pole motor : F_{max} = 6 kHz (360,000 cpm), 1600 FFT lines, 8 average
  - 2 pole motor : F_{max} = 4 kHz (240,000 cpm), 1600 FFT lines, 8 average
  - Detection of RBPF and its harmonics
  - 회전자 봉의 수를 모르는 경우는 높은 주파수 영역에서 $2F_L$ 성분의 측대역 성분 발생에 주목