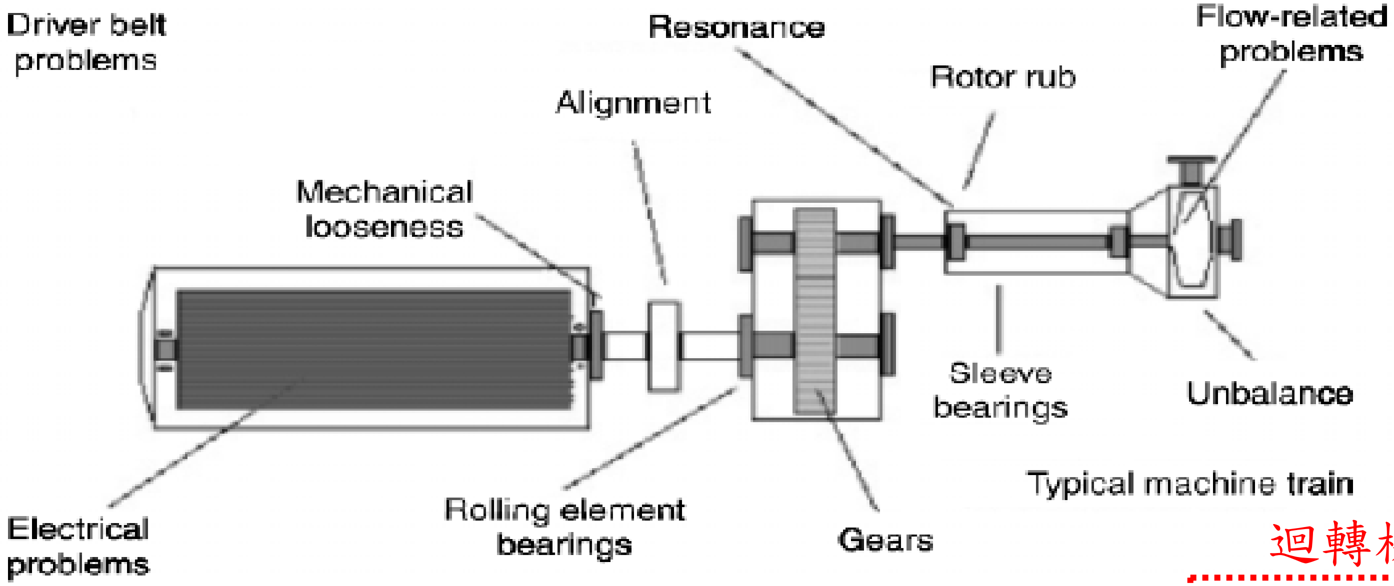
時頻分析於迴轉機械之振噪檢測訓練課程

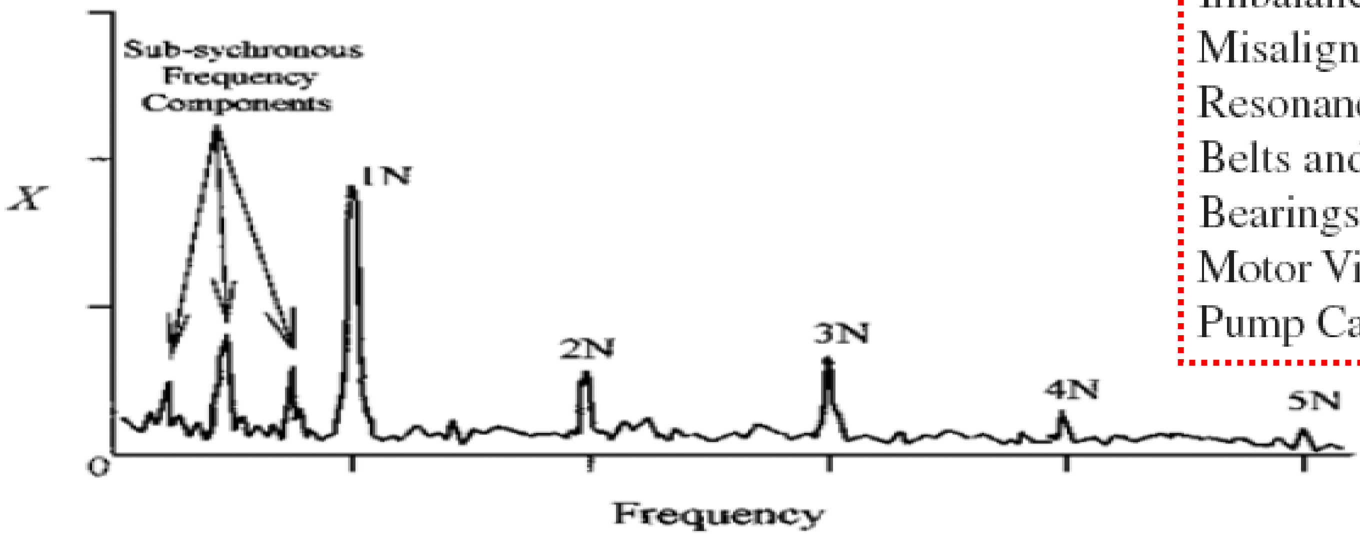
旋轉機械之異常振動診斷理論基礎

吳豐泰

逸奇科技

迴轉機械之傳動與典型振動頻譜

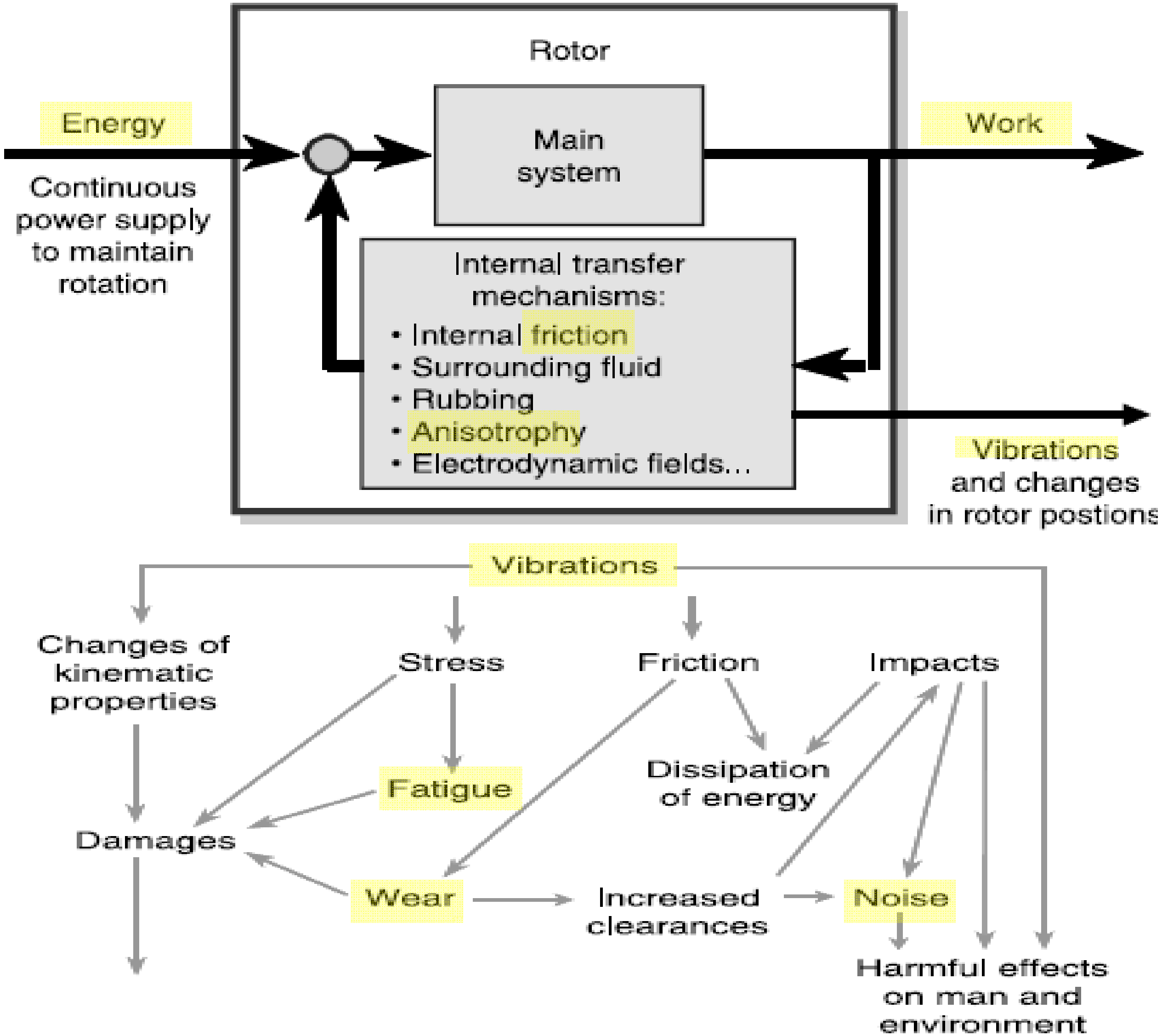




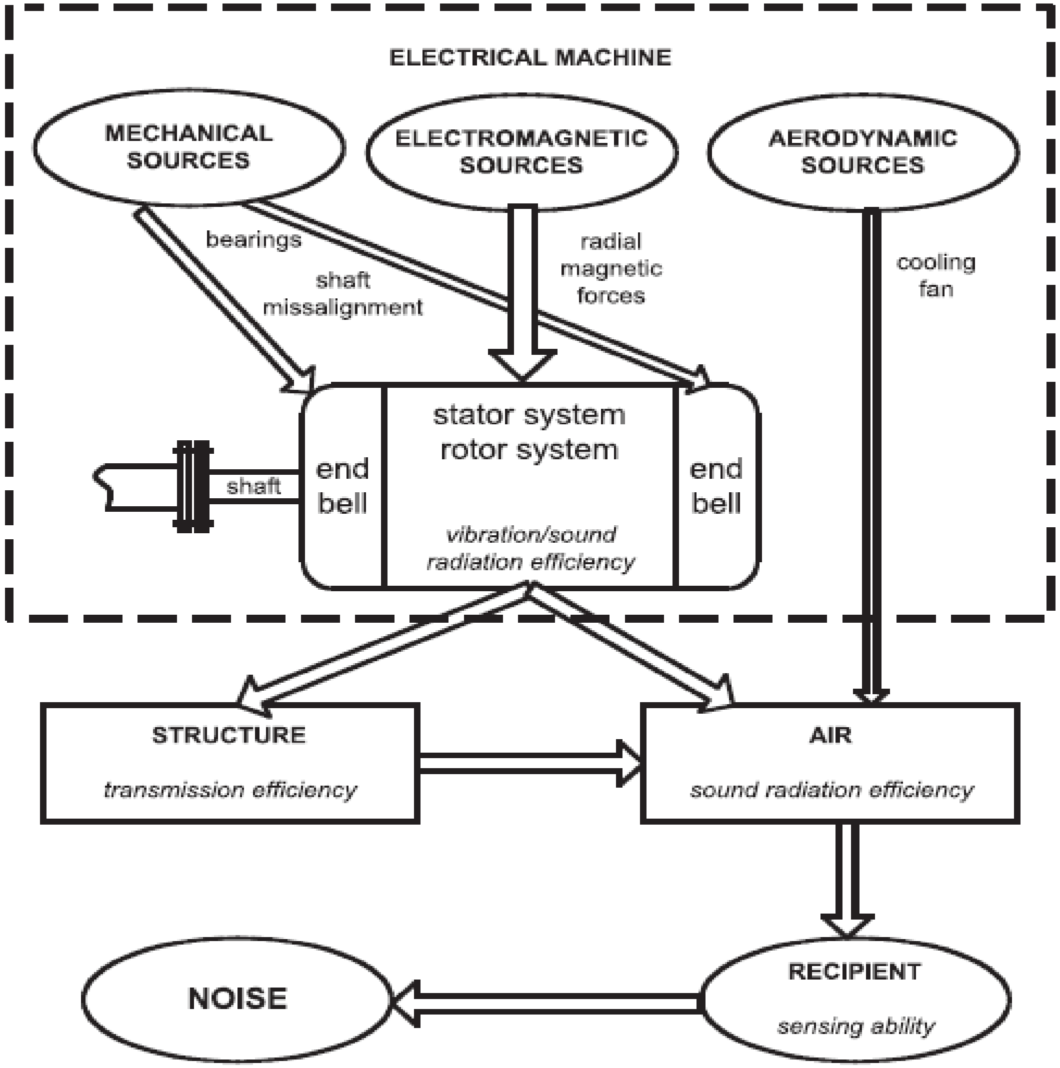
迴轉機械異常原因排序

Imbalance	40%
Misalignment	30%
Resonance	20%
Belts and Pulleys	30%
Bearings	10%
Motor Vibration	8%
Pump Cavitation	5%

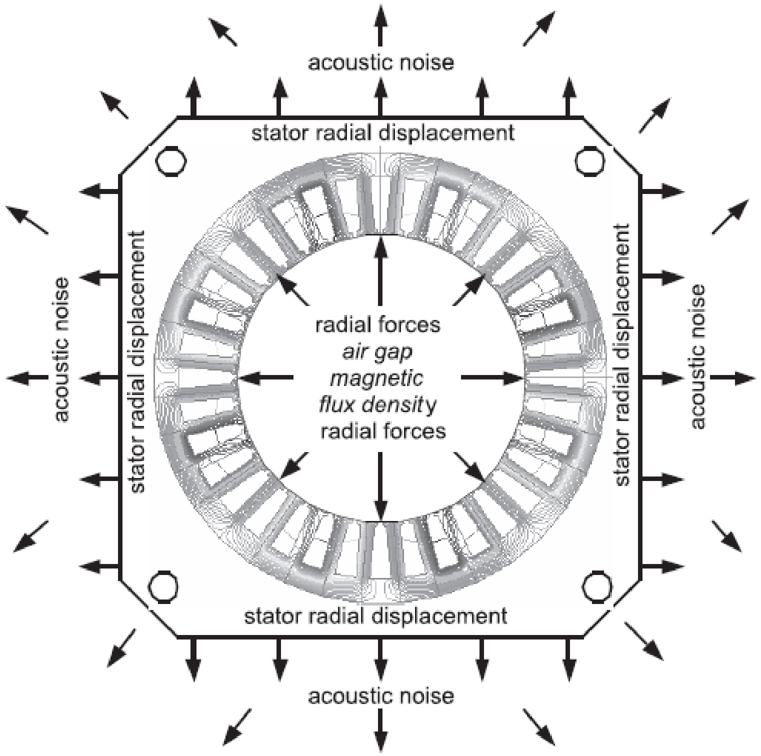
迴轉機械之振動與噪音之原因



振動與噪音之關連

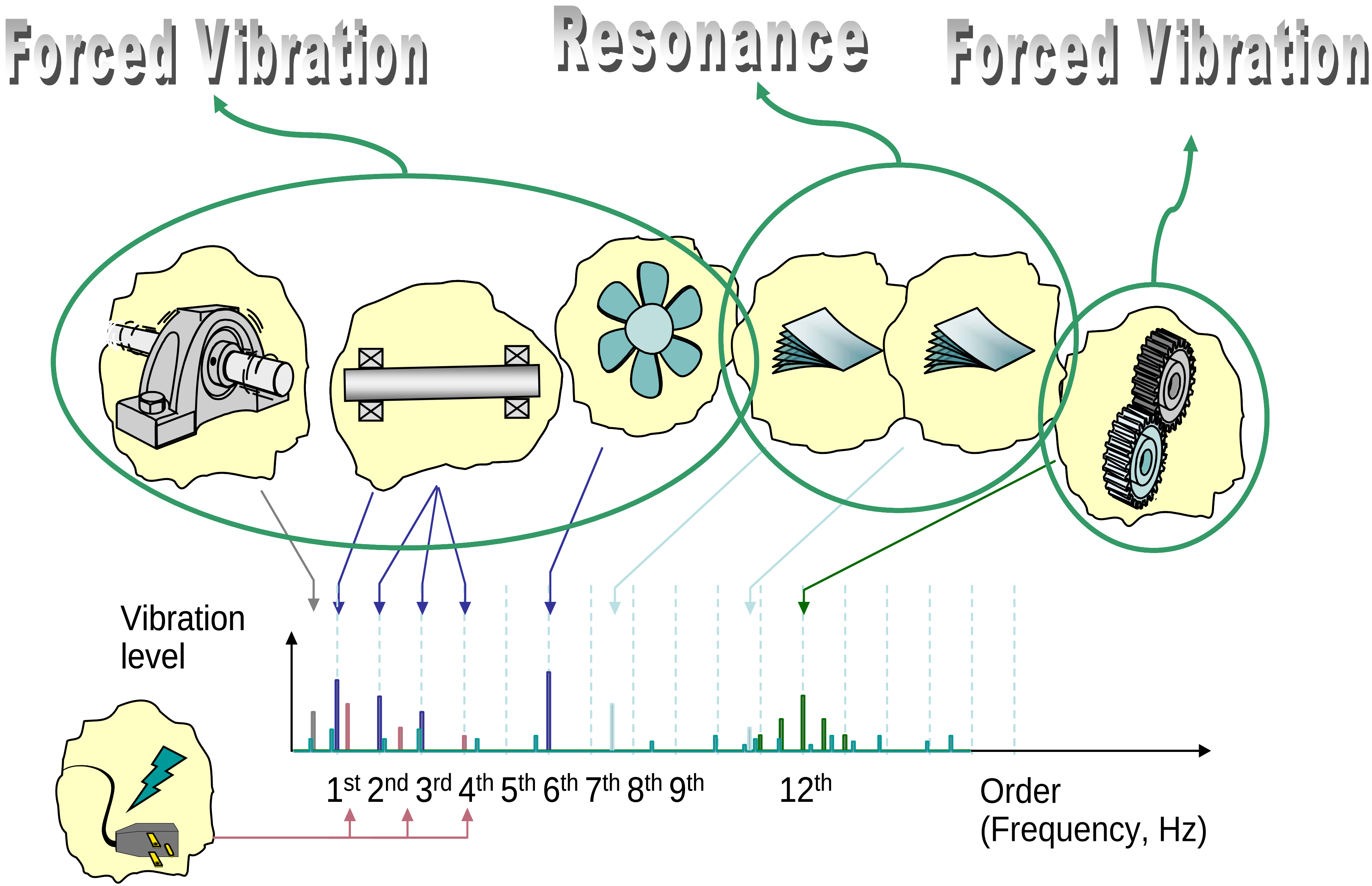


ELECTRICAL MACHINE
MECHANICAL SOURCES
ELECTROMAGNETIC SOURCES
AERODYNAMIC SOURCES
bearings
shaft missalignment
radial magnetic forces
cooling fan
stator system
rotor system
shaft
end bell
end bell
vibration/sound radiation efficiency
STRUCTURE
transmission efficiency
AIR
sound radiation efficiency
RECIPIENT
sensing ability
NOISE



acoustic noise
stator radial displacement
radial forces
air gap
magnetic
flux density
radial forces
stator radial displacement
acoustic noise
acoustic noise
stator radial displacement
stator radial displacement
acoustic noise

迴轉機械之轉速倍頻振動頻譜



偏心振動

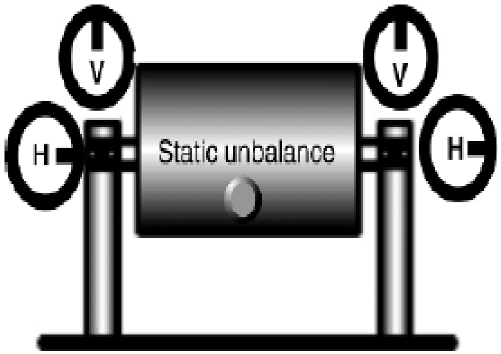


Figure 5.2
Phase relationship – static unbalance

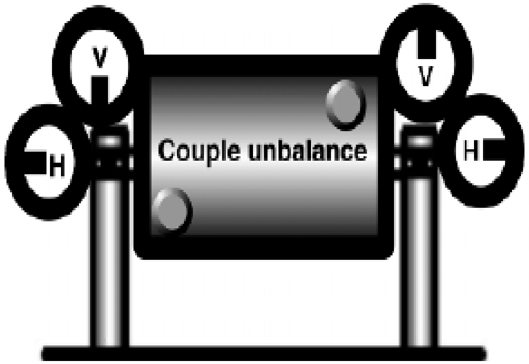


Figure 5.3
Phase relationship – couple unbalance

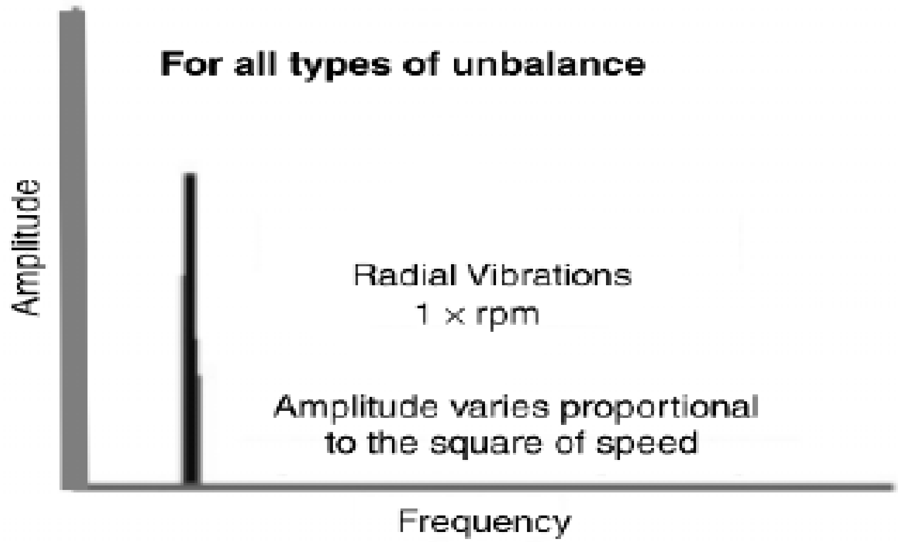


Figure 5.1
FFT analysis – unbalance defect

轉軸彎曲變形效應

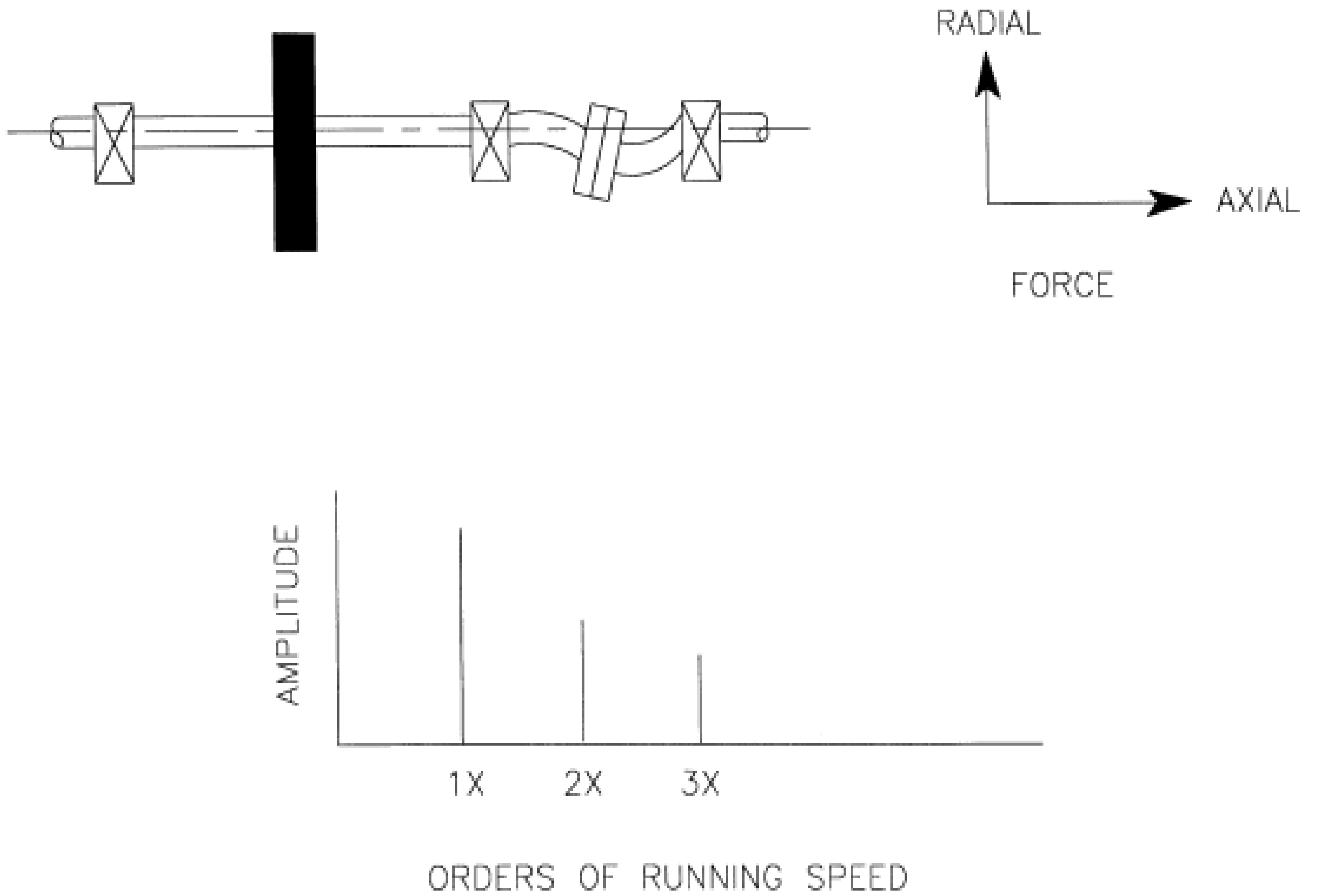


Figure 15.32 Bends that change shaft length generate axial thrust.

轉軸對心問題：角度

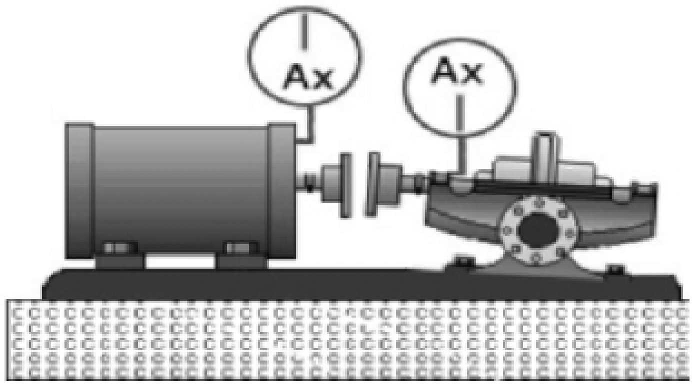


Figure 5.11
Angular misalignment confirmed by phase analysis

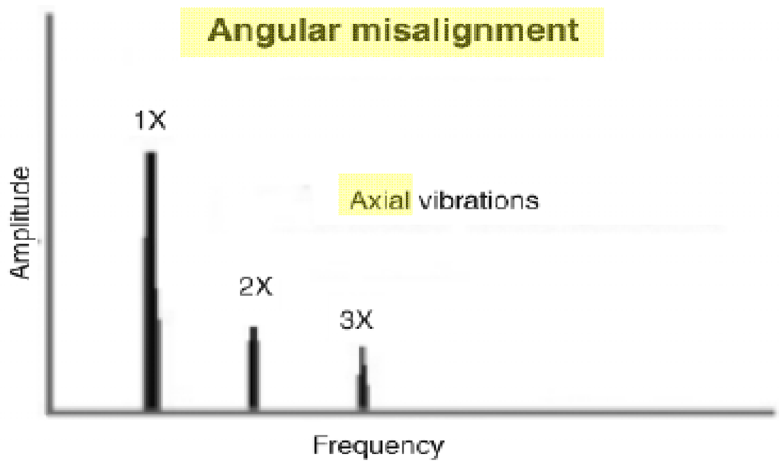


Figure 5.10
FFT of angular misalignment

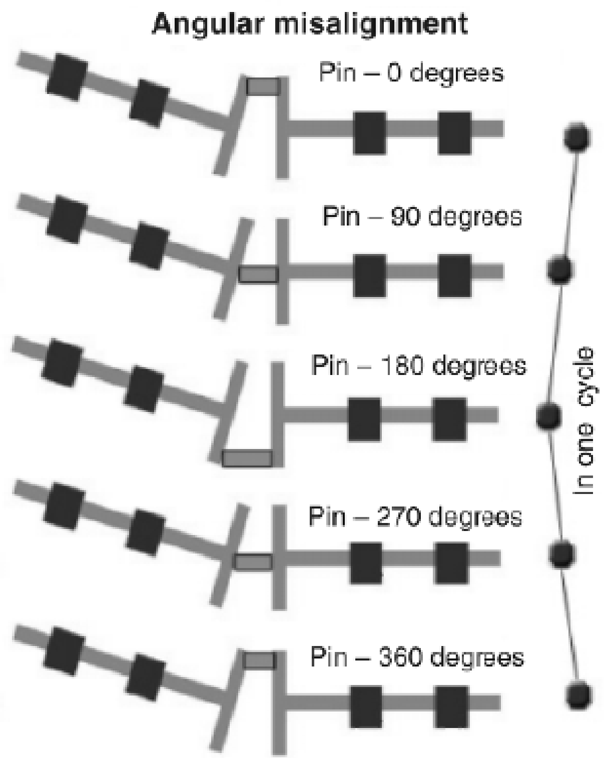


Figure 5.9
Angular misalignment

轉軸對心問題：平行

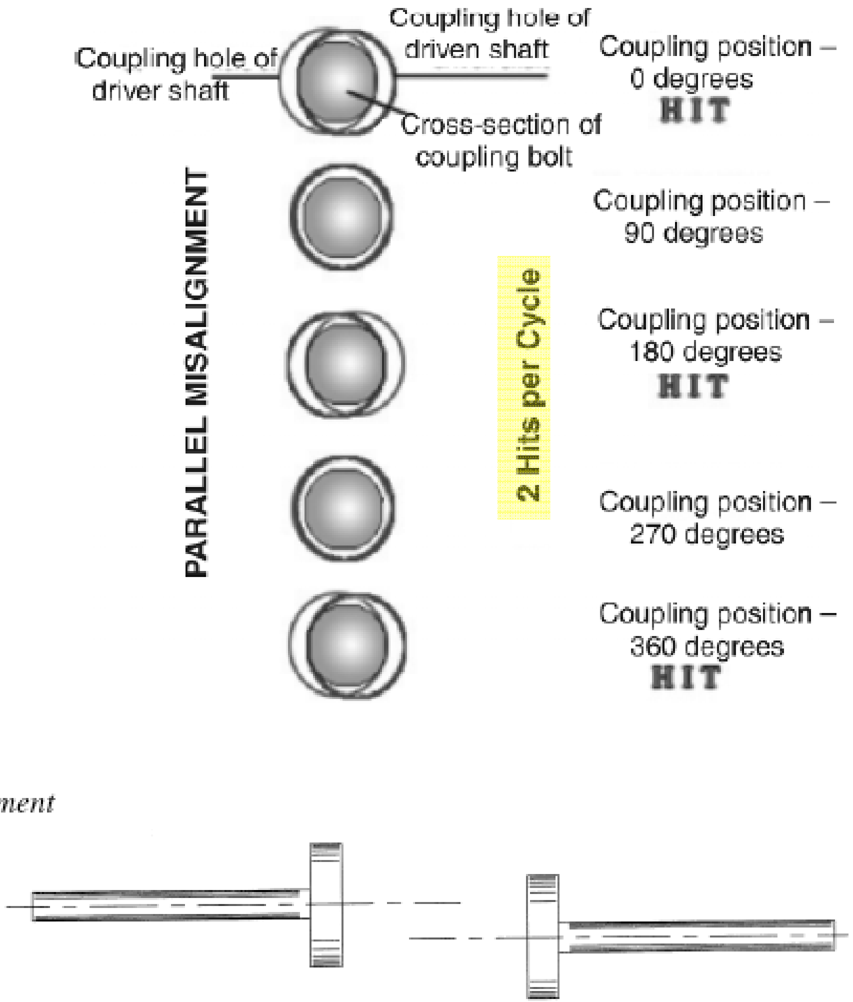


Figure 5.12
Parallel misalignment

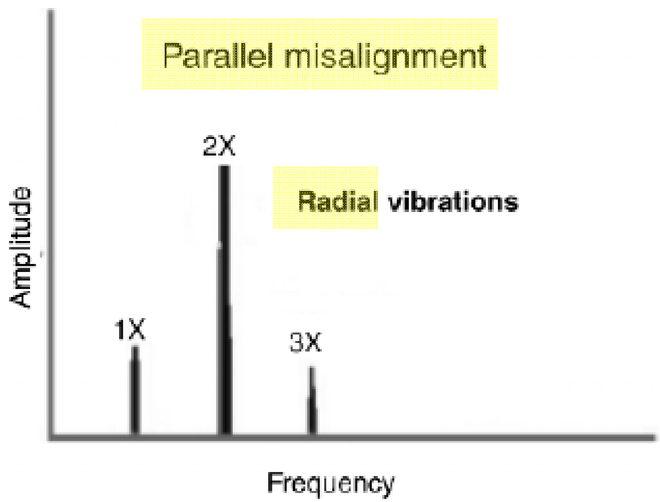


Figure 5.13
FFT of parallel misalignment

鬆脫問題：軸承裝配

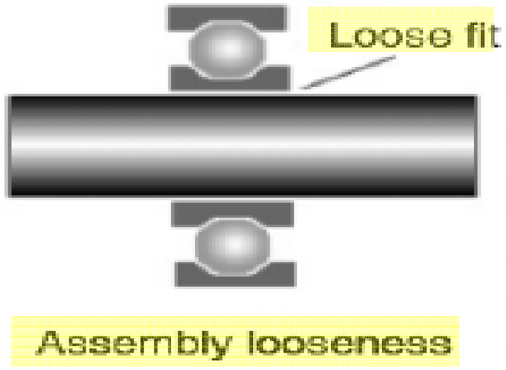


Figure 5.19
Loose fit

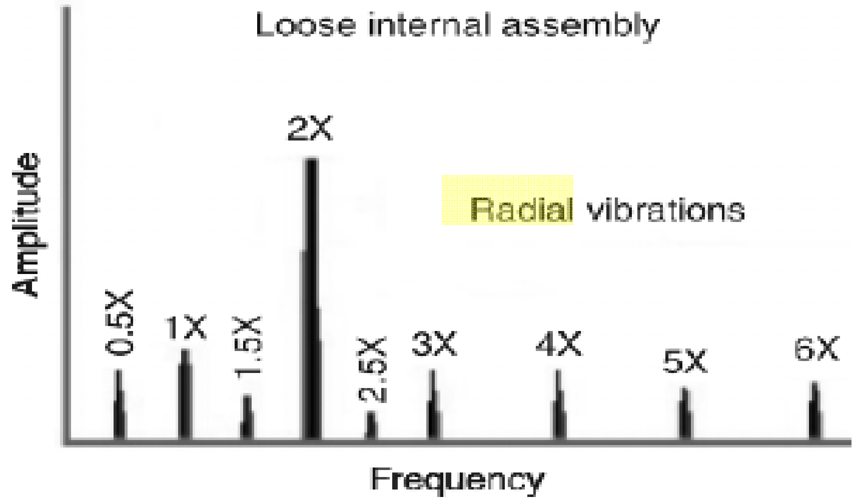


Figure 5.18
Loose internal assembly graph

鬆脫問題：基座裝配

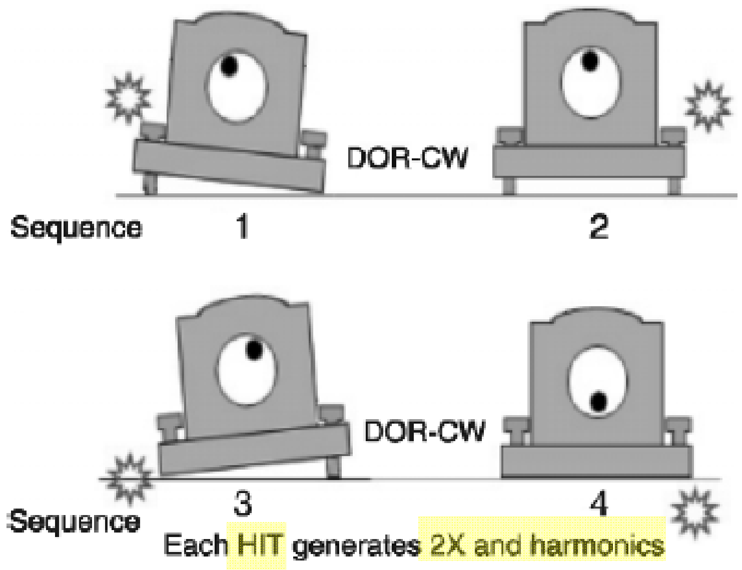


Figure 5.21
Mechanical looseness

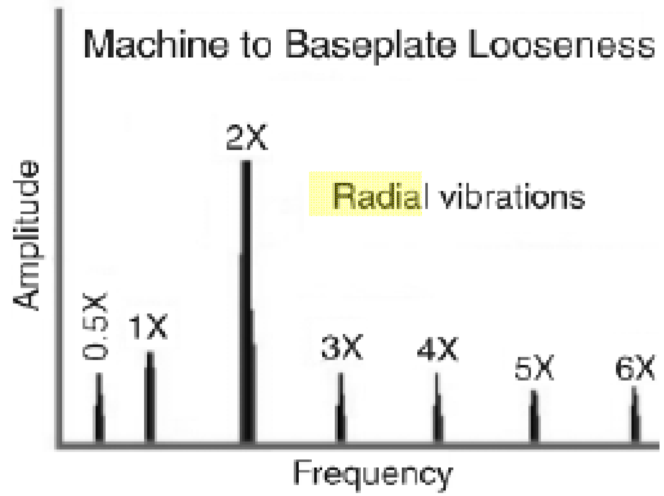


Figure 5.20
Mechanical looseness graph

鬆脫問題：基座鬆軟

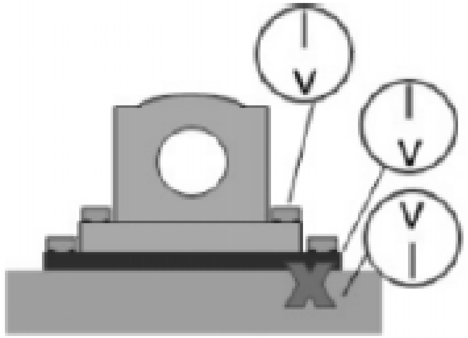


Figure 5.22
Structure looseness

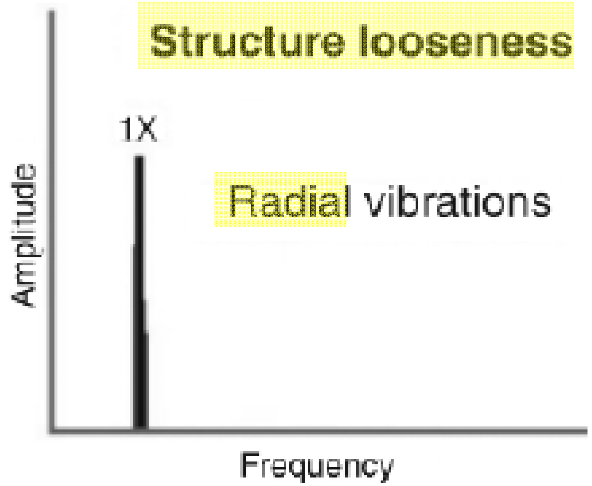


Figure 5.23
Structure looseness graph

轉子摩擦

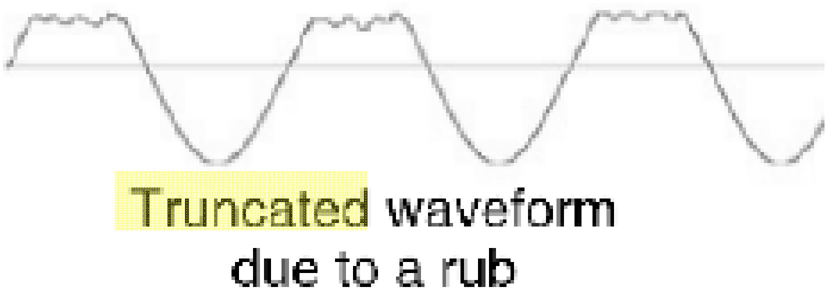


Figure 5.37
Truncated waveform

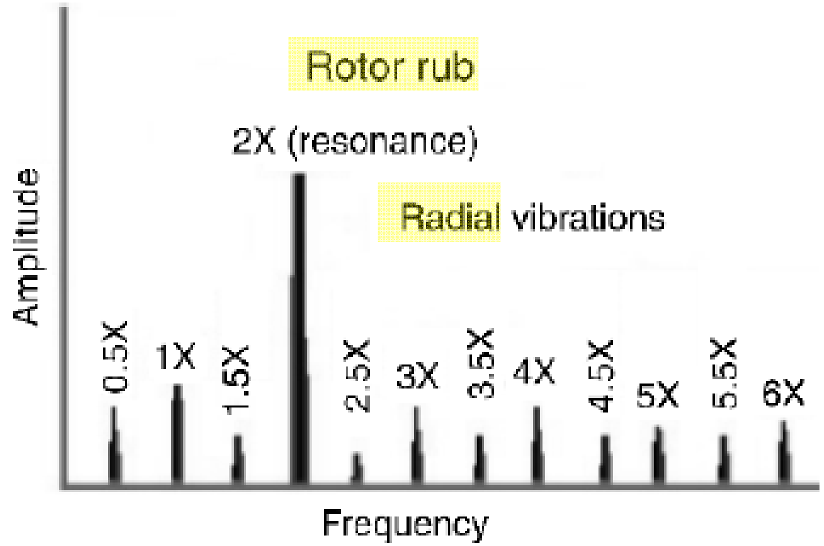
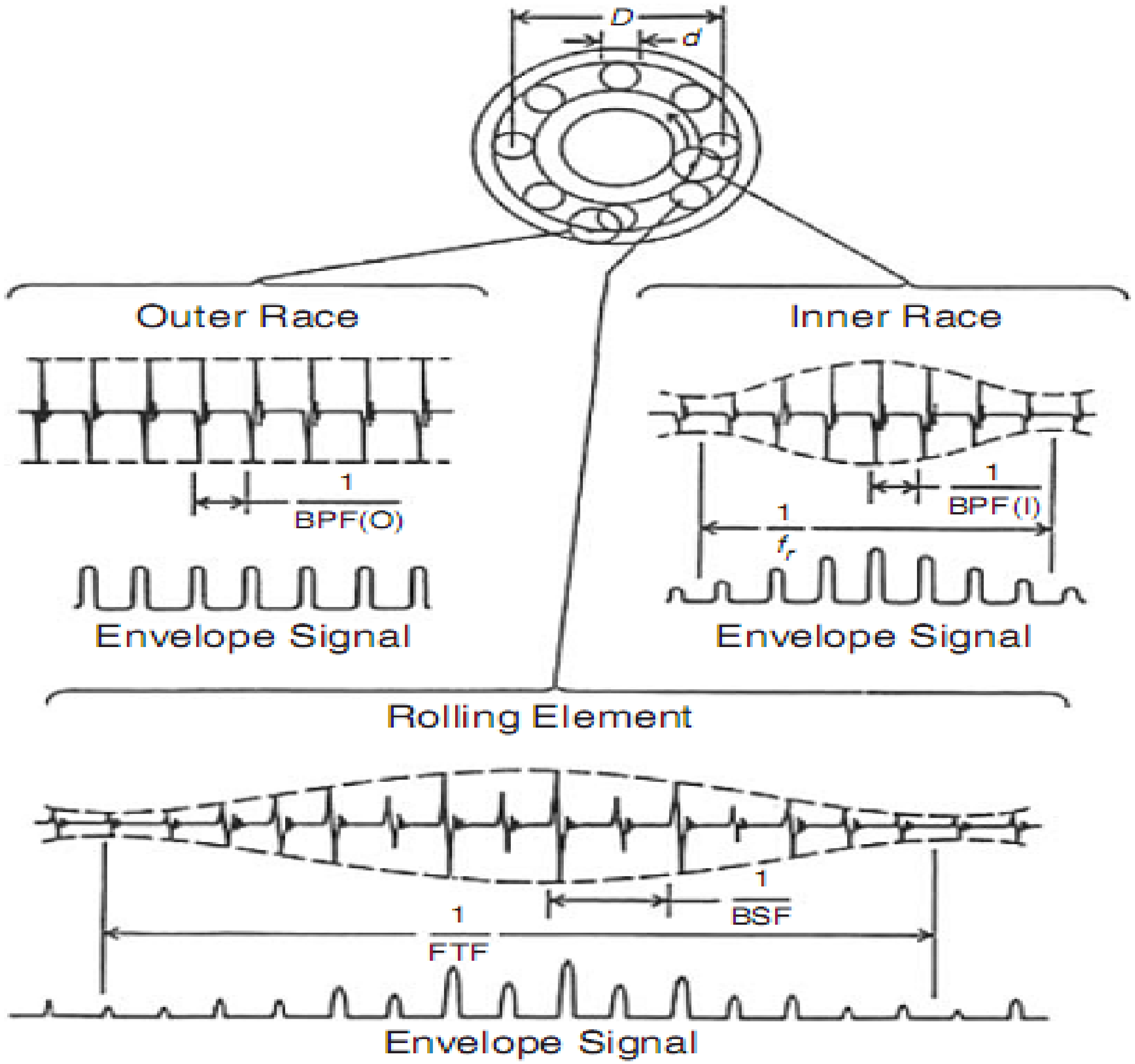


Figure 5.36
Rotor rub

軸承異常振動波形


D
d
Outer Race
1
BPF(O)
Envelope Signal
Inner Race
1
BPF(I)
1
f_r
Envelope Signal
Rolling Element
1
BSF
1
FTF
Envelope Signal

軸承於正常狀態下之振動頻譜

Zone A: machine rpm and harmonics zone
Zone B: bearing defect frequencies zone (5–30 kcpm)
Zone C: bearing component natural frequencies zone (30–120 kcpm)
Zone D: high-frequency-detection (HFD) zone (beyond 120 kcpm).

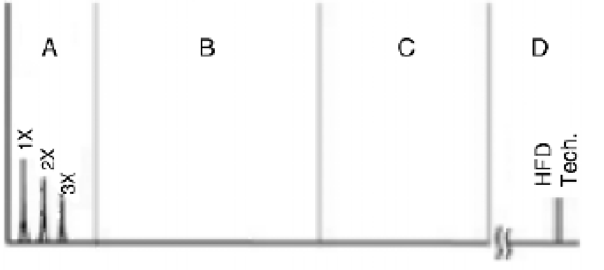


Figure 5.44
Small defects in the raceways of a bearing

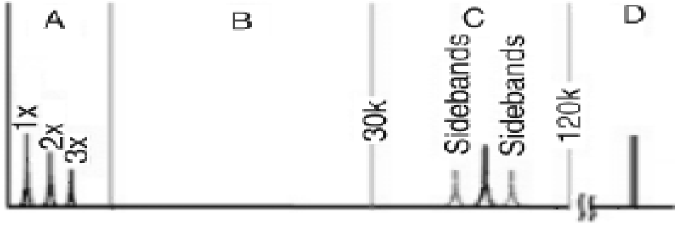


Figure 5.45
More obvious wear in the form of pits

軸承於磨損狀態下之振動頻譜

$$BPFI = \frac{Nb}{2}\left(1 + \frac{Bd}{Pd}\cos\theta\right) \times rpm$$

$$BPFO = \frac{Nb}{2}\left(1 - \frac{Bd}{Pd}\cos\theta\right) \times rpm$$

$$FTF = \frac{1}{2}\left(1 - \frac{Bd}{Pd}\cos\theta\right) \times rpm$$

$$BSF = \frac{Pd}{2Bd}\left[1 - \left(\frac{Bd}{Pd}\right)^2 (\cos\theta)^2\right] \times rpm$$

Nb = Number of Balls or Rollers
Bd = Ball / Roller diameter (inch or mm)
Pd = Bearing pitch diameter (inch or mm)
θ = Contact angle in degrees

BPFI = Ball pass frequency – Inner
BPFO = Ball pass frequency – Outer
FTF = Fundamental train frequency (Cage)
BSF = Ball spin frequency (rolling element)

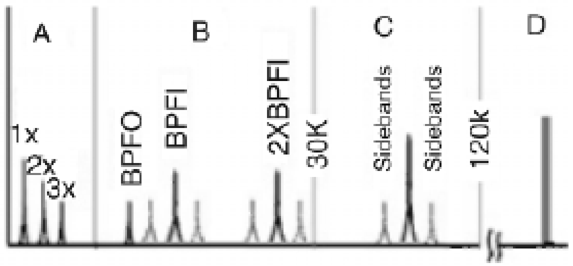


Figure 5.46
Wear is now clearly visible over the breadth of the bearing

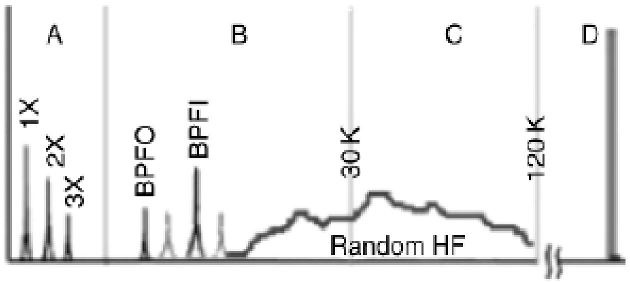
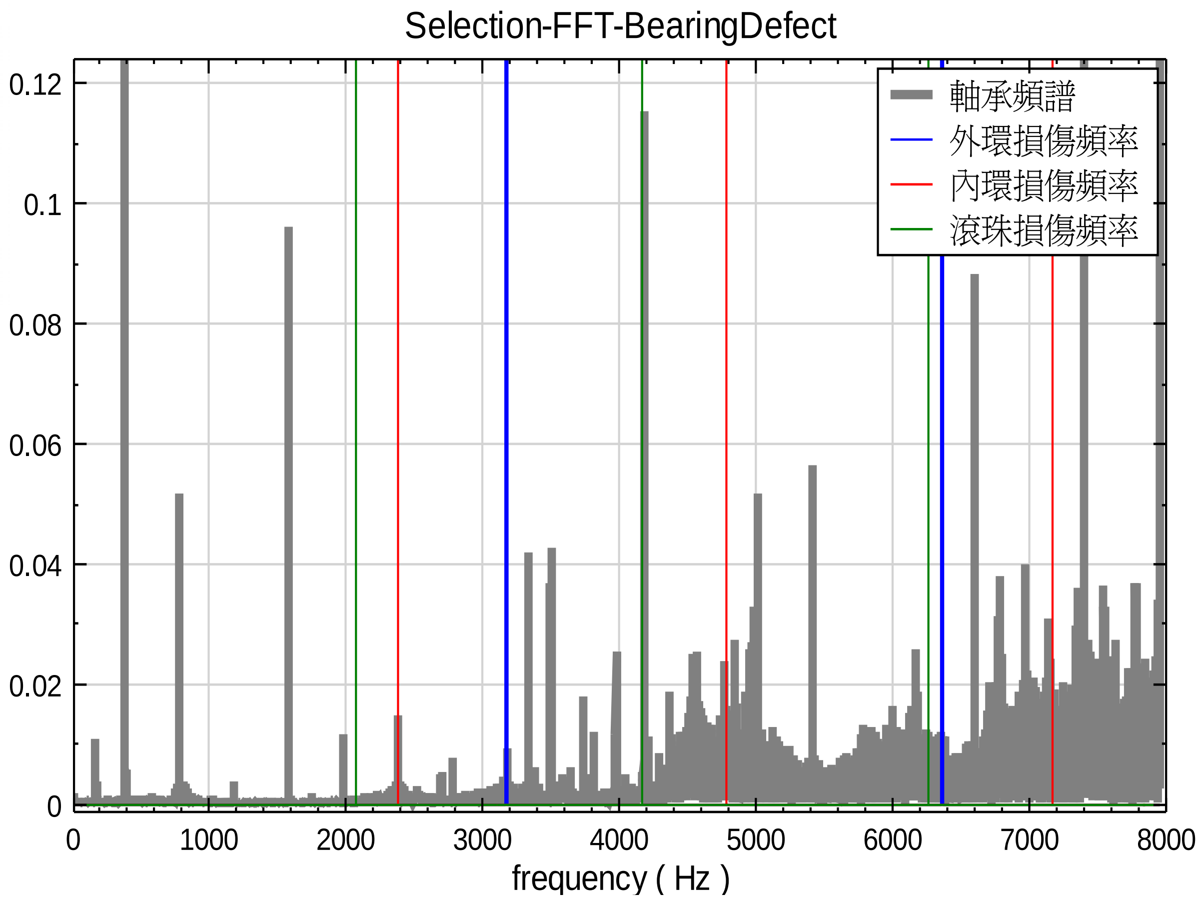


Figure 5.47
Severely damaged bearing in final stage of wear

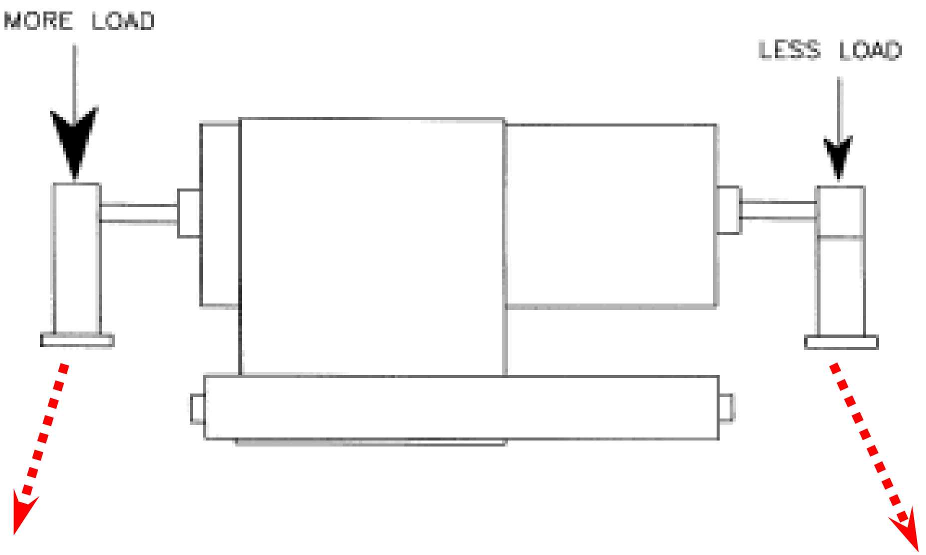
軸承之損壞特徵檢測

依據軸承規格自動計算內外環或滾珠損壞特徵頻率

特徵頻率	
內環損傷頻率	2392.9923728949975
外環損傷頻率	3184.6076271050019
滾珠損傷頻率	2089.5379498952088
參數	
轉速	398.4
軸承規格	
軸承平均直徑	42.5
接觸角	15
滾珠直徑	7.94
滾珠數量	14

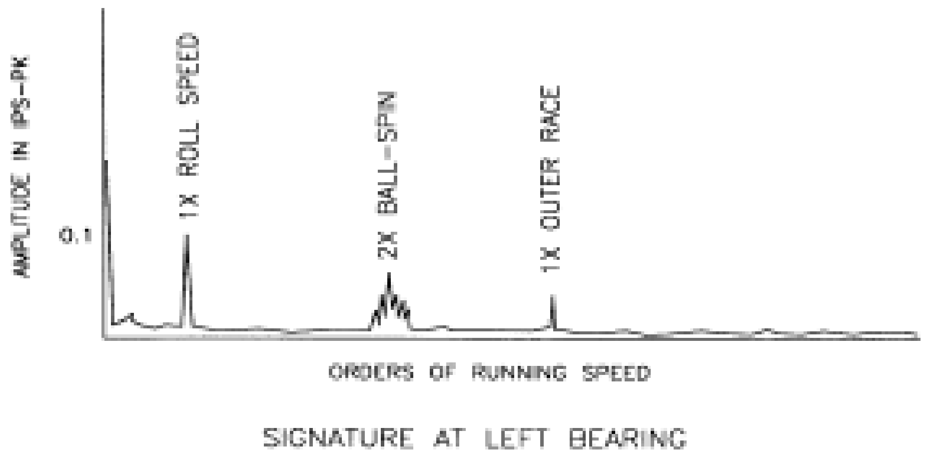


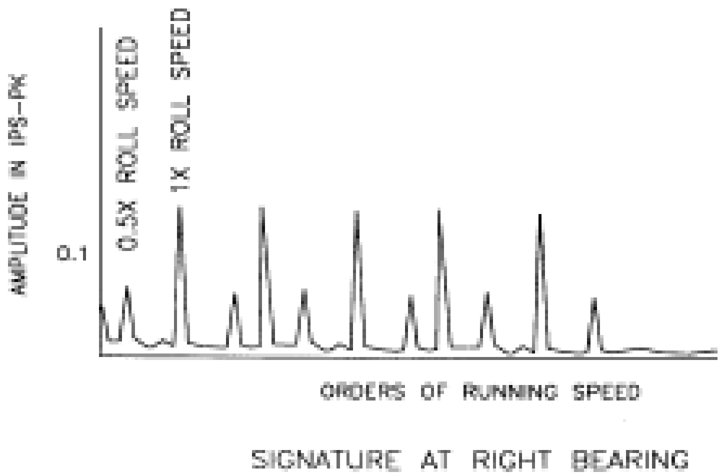
軸承受力不均之頻譜特徵



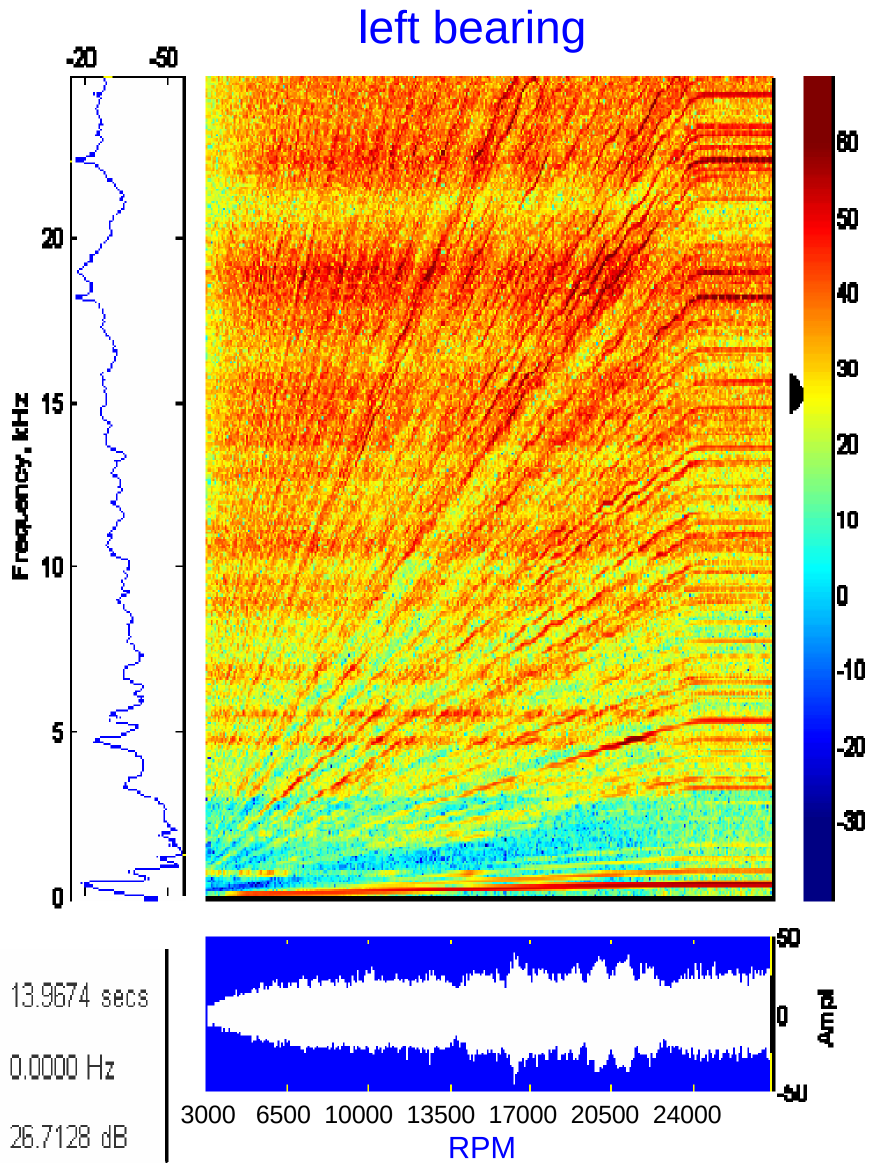
受力較大：軸承相關之高頻振動

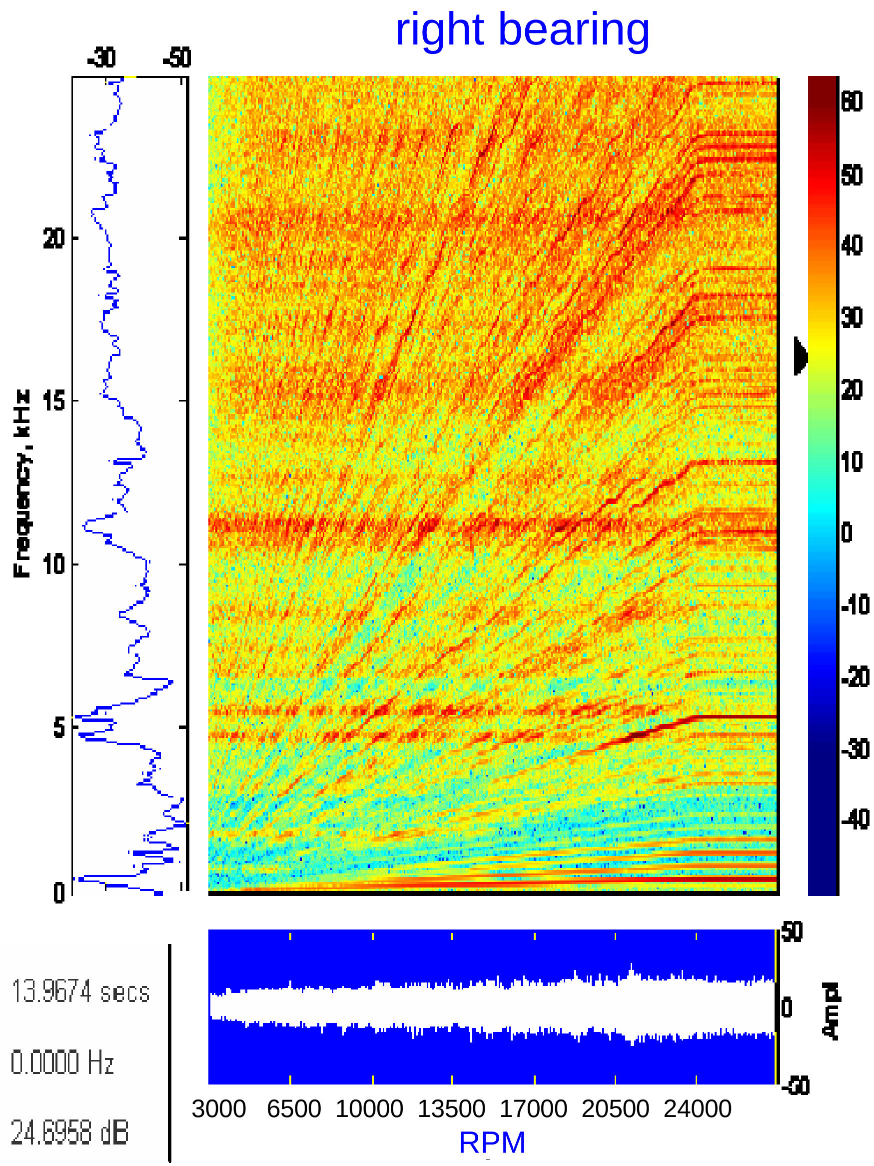
受力較小：轉速相關之低頻振動



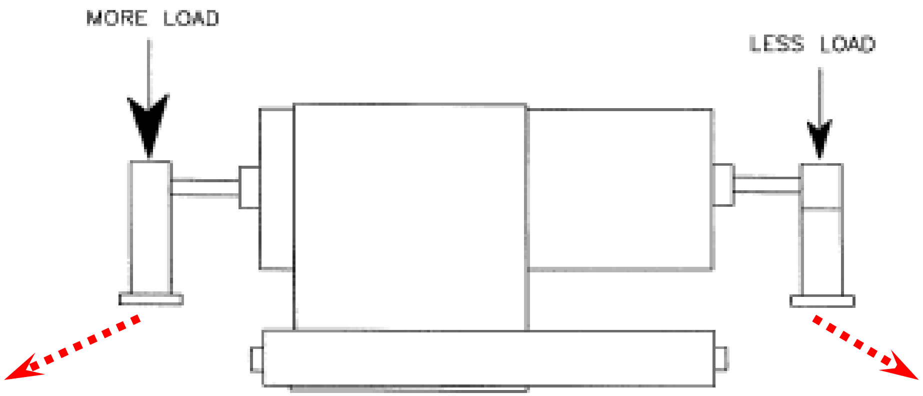


軸承受力不均之變轉速時頻分析

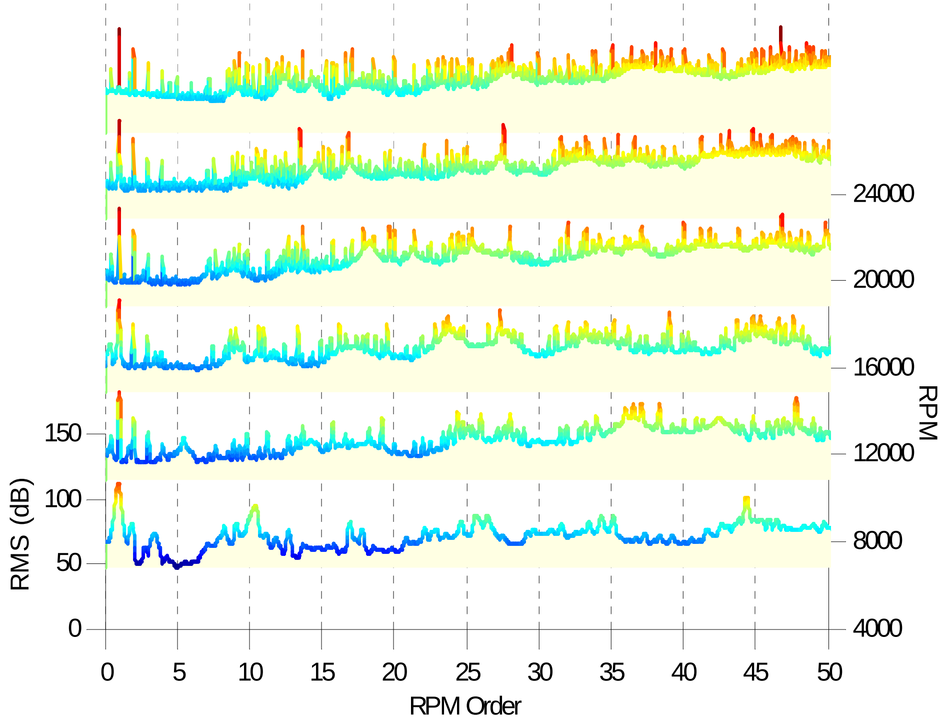




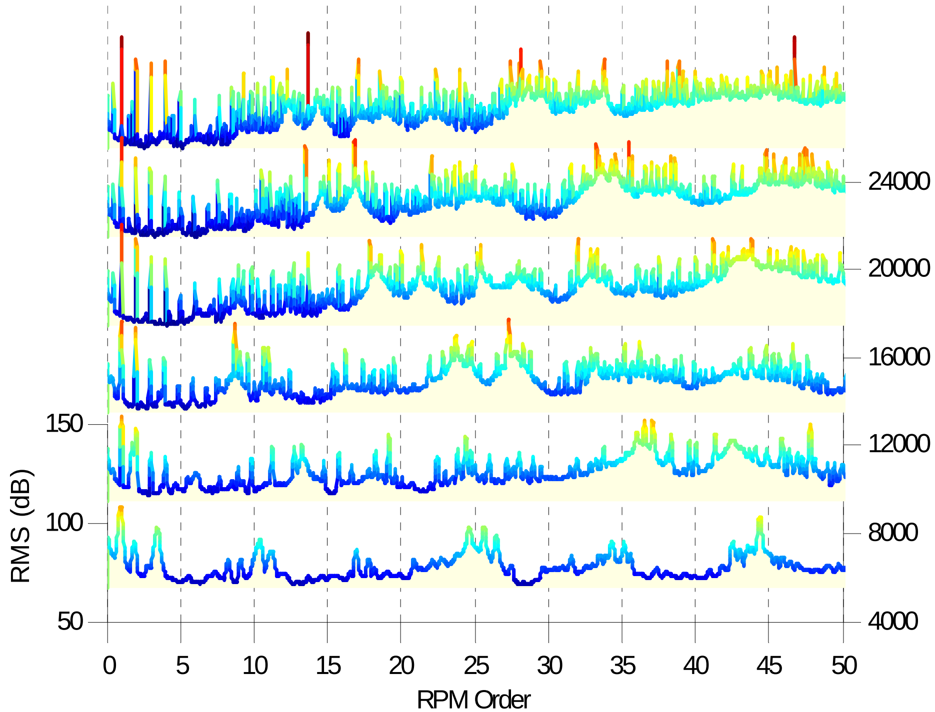
軸承受力不均之階次頻譜分析



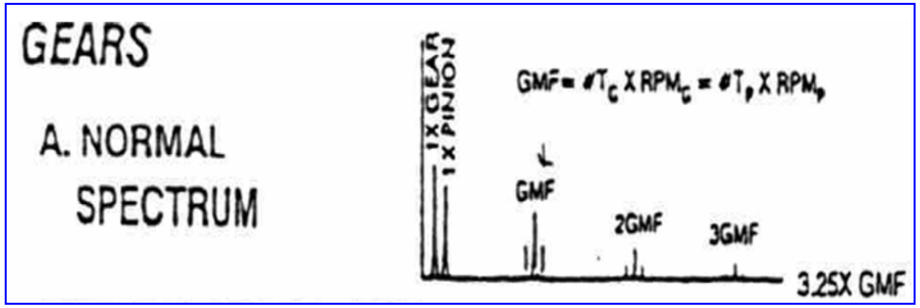
受力較大：軸承相關之高頻振動

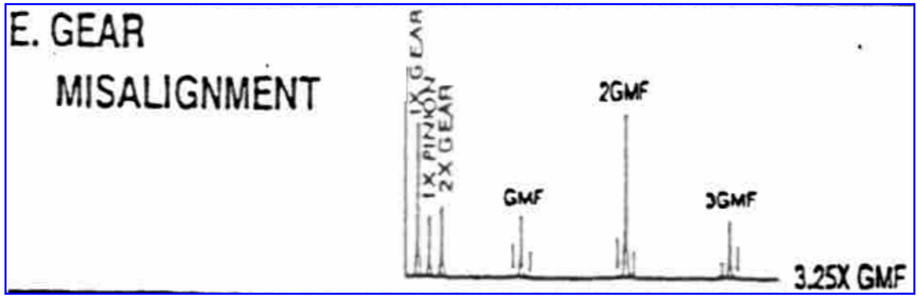


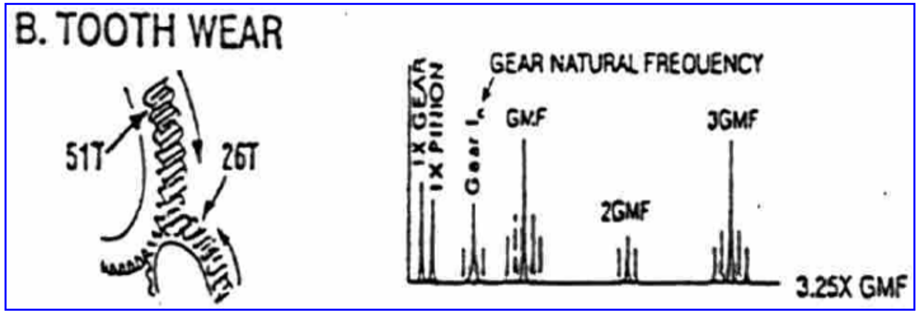
受力較小：轉速相關之低頻振動

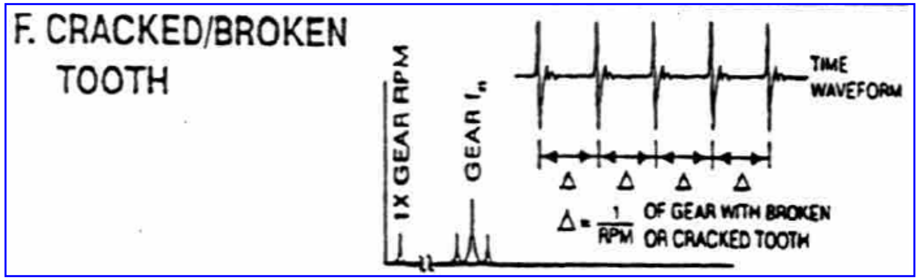


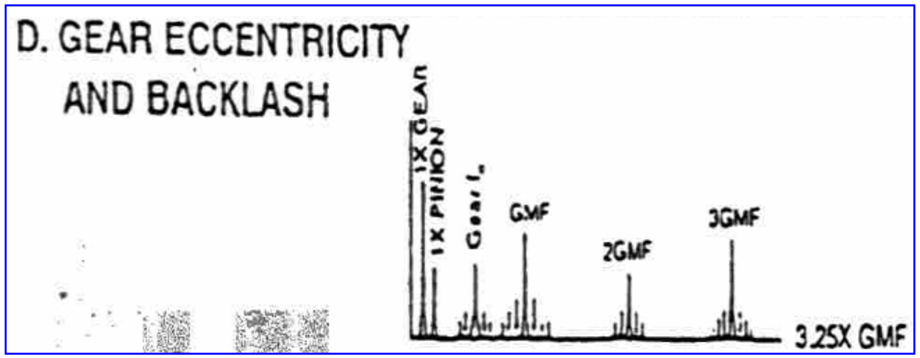
齒輪異常振動頻譜

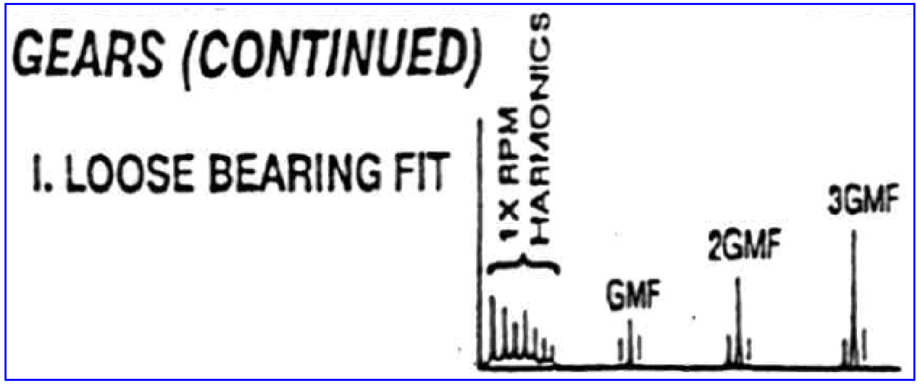

GEARS
A. NORMAL
SPECTRUM
1X GEAR
1X PINION
GMF = #T_G X RPM_G = #T_P X RPM_P
GMF
2GMF
3GMF
3.25X GMF


E. GEAR
MISALIGNMENT
1X GEAR
1X PINION
2X GEAR
GMF
2GMF
3GMF
3.25X GMF


B. TOOTH WEAR
51T
26T
1X GEAR
1X PINION
Gear f_n
GEAR NATURAL FREQUENCY
GMF
2GMF
3GMF
3.25X GMF


F. CRACKED/BROKEN
TOOTH
1X GEAR RPM
GEAR f_n
TIME
WAVEFORM
Δ Δ Δ Δ
Δ = 1/RPM OF GEAR WITH BROKEN OR CRACKED TOOTH


D. GEAR ECCENTRICITY
AND BACKLASH
1X GEAR
1X PINION
Gear f_n
GMF
2GMF
3GMF
3.25X GMF


GEARS (CONTINUED)
I. LOOSE BEARING FIT
1X RPM
HARMONICS
GMF
2GMF
3GMF

齒輪振動頻譜-正常邊頻狀態

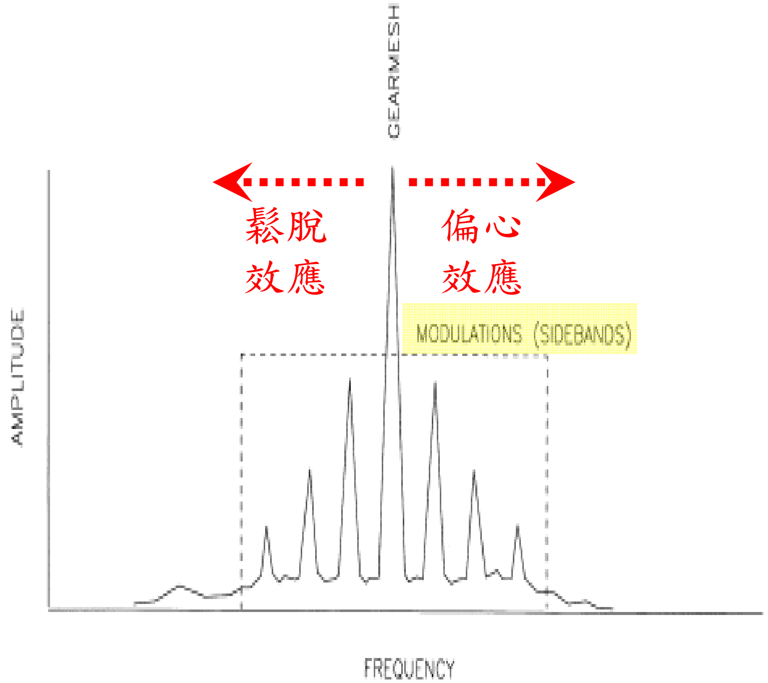


Figure 15.16 Normal gear set profile is symmetrical.

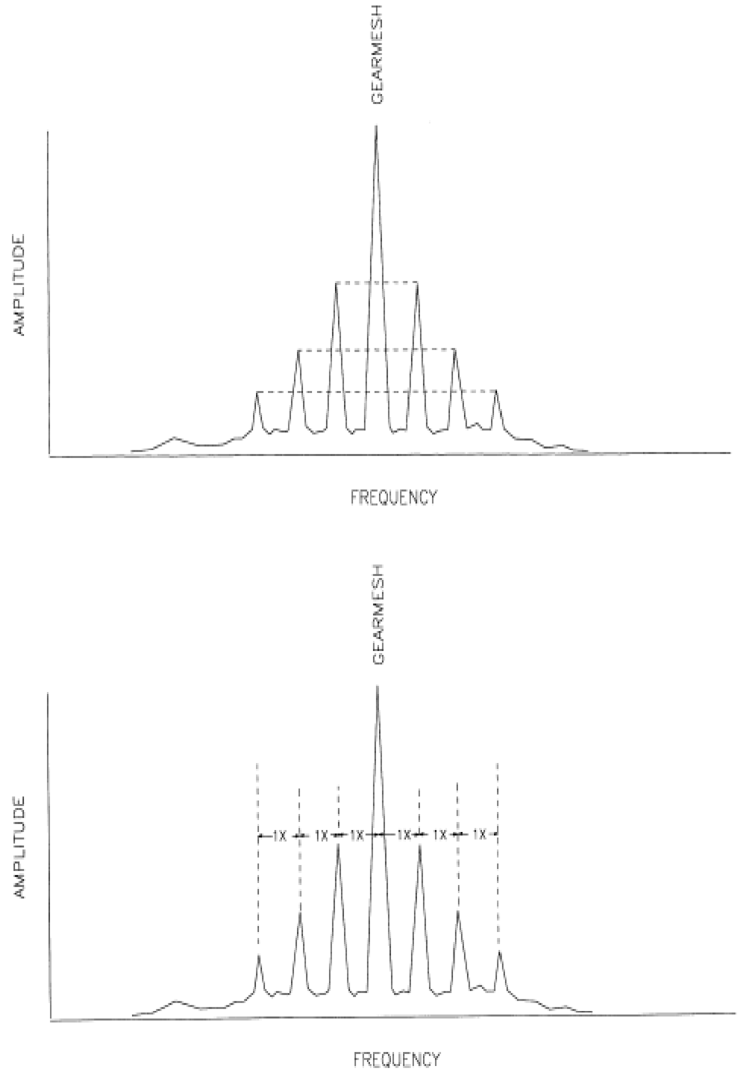


Figure 15.17 Sidebands are paired and equal.

齒輪振動頻譜-異常邊頻狀態

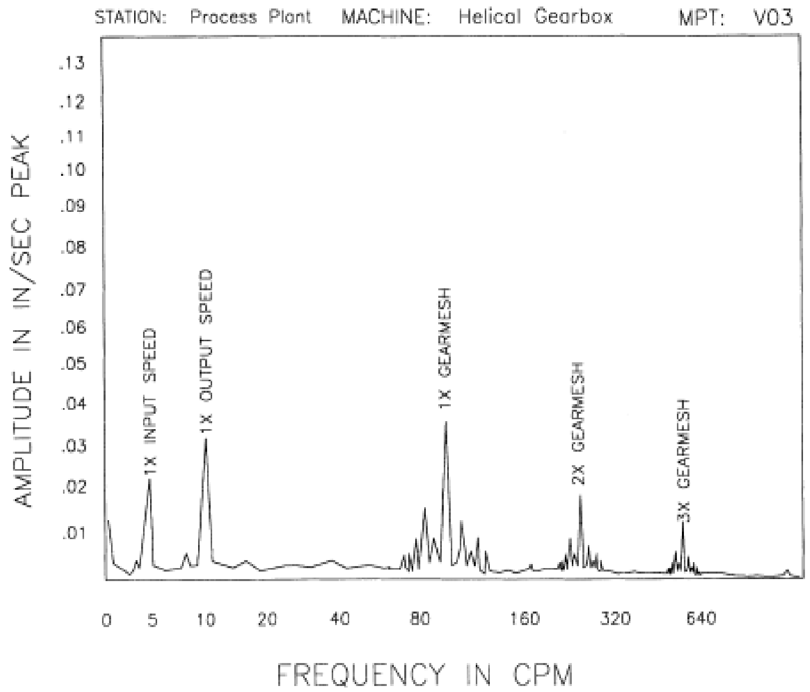


Figure 15.18 Typical defective gear-mesh signature.

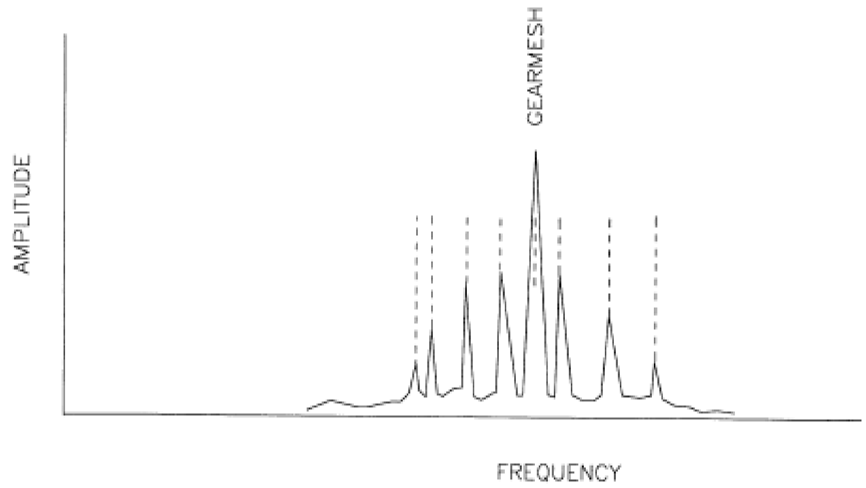


Figure 15.19 Wear or excessive clearance changes the sideband spacing.

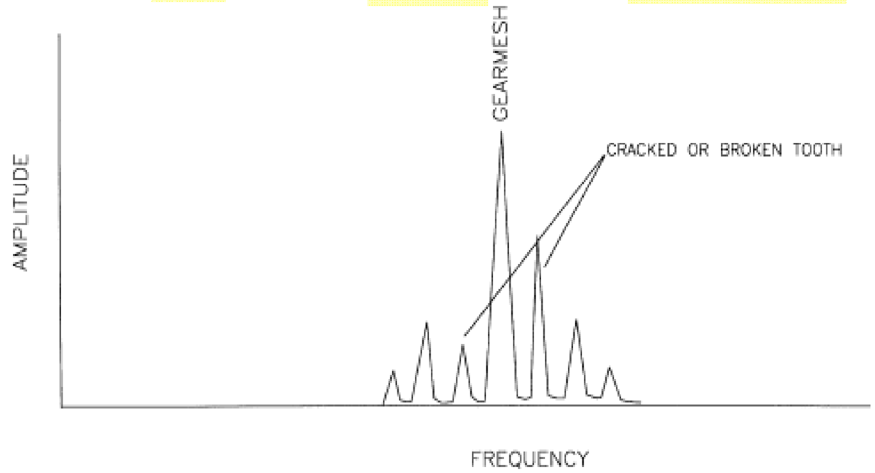
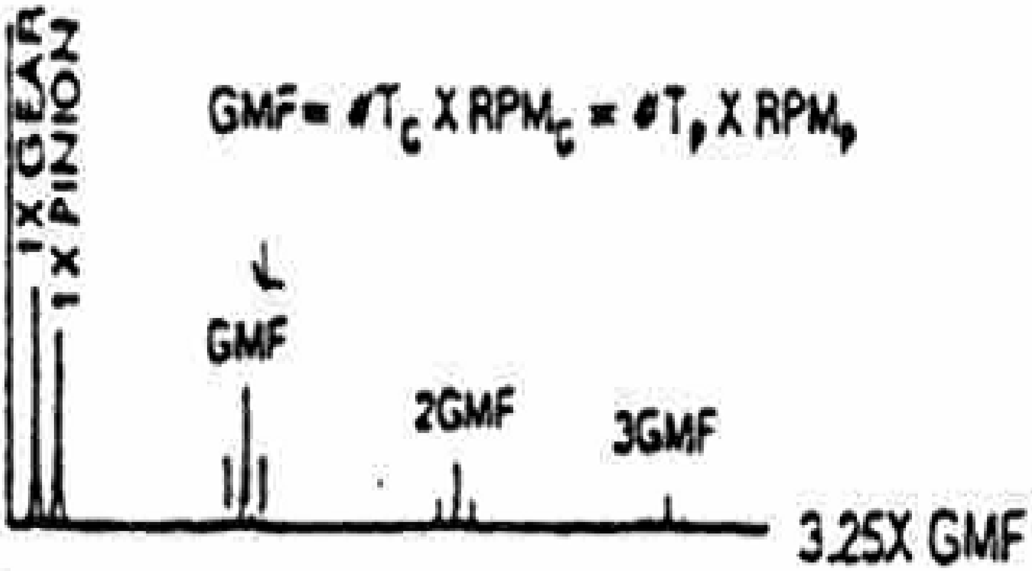
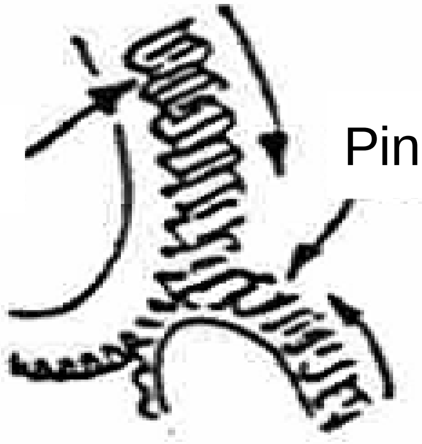


Figure 15.20 A broken tooth will produce an asymmetrical sideband profile.

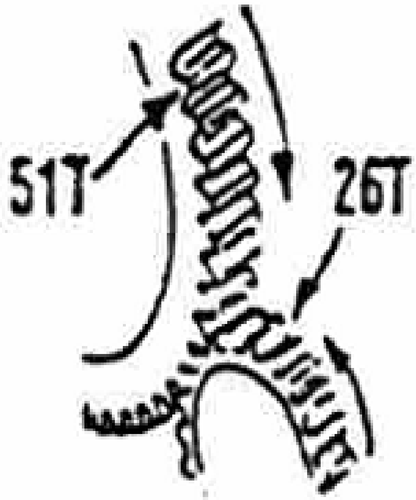
GEARS

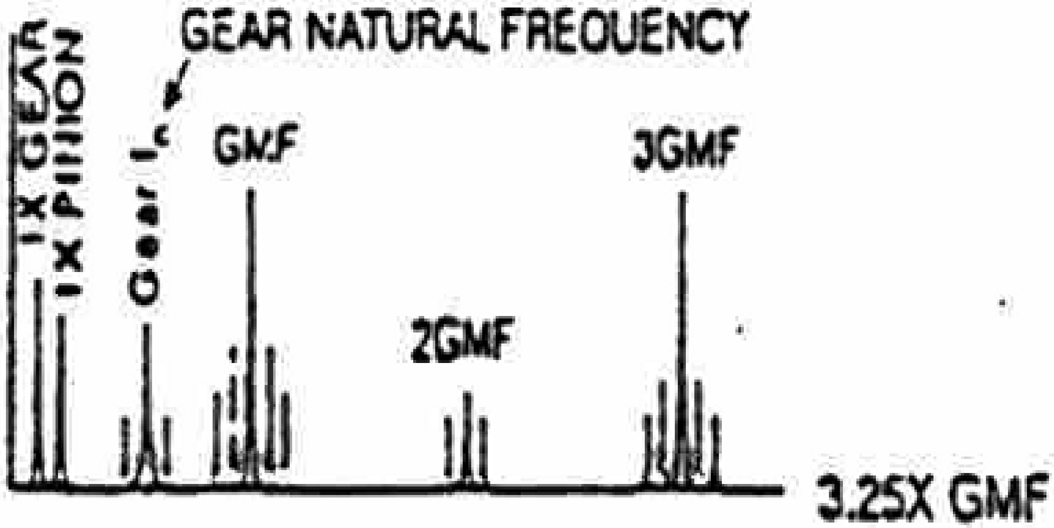
A. NORMAL SPECTRUM

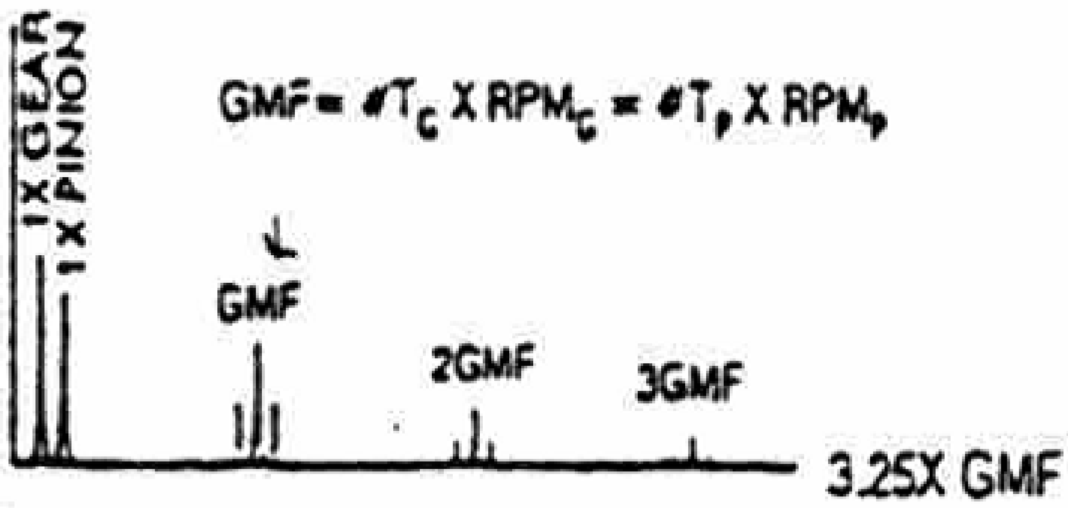




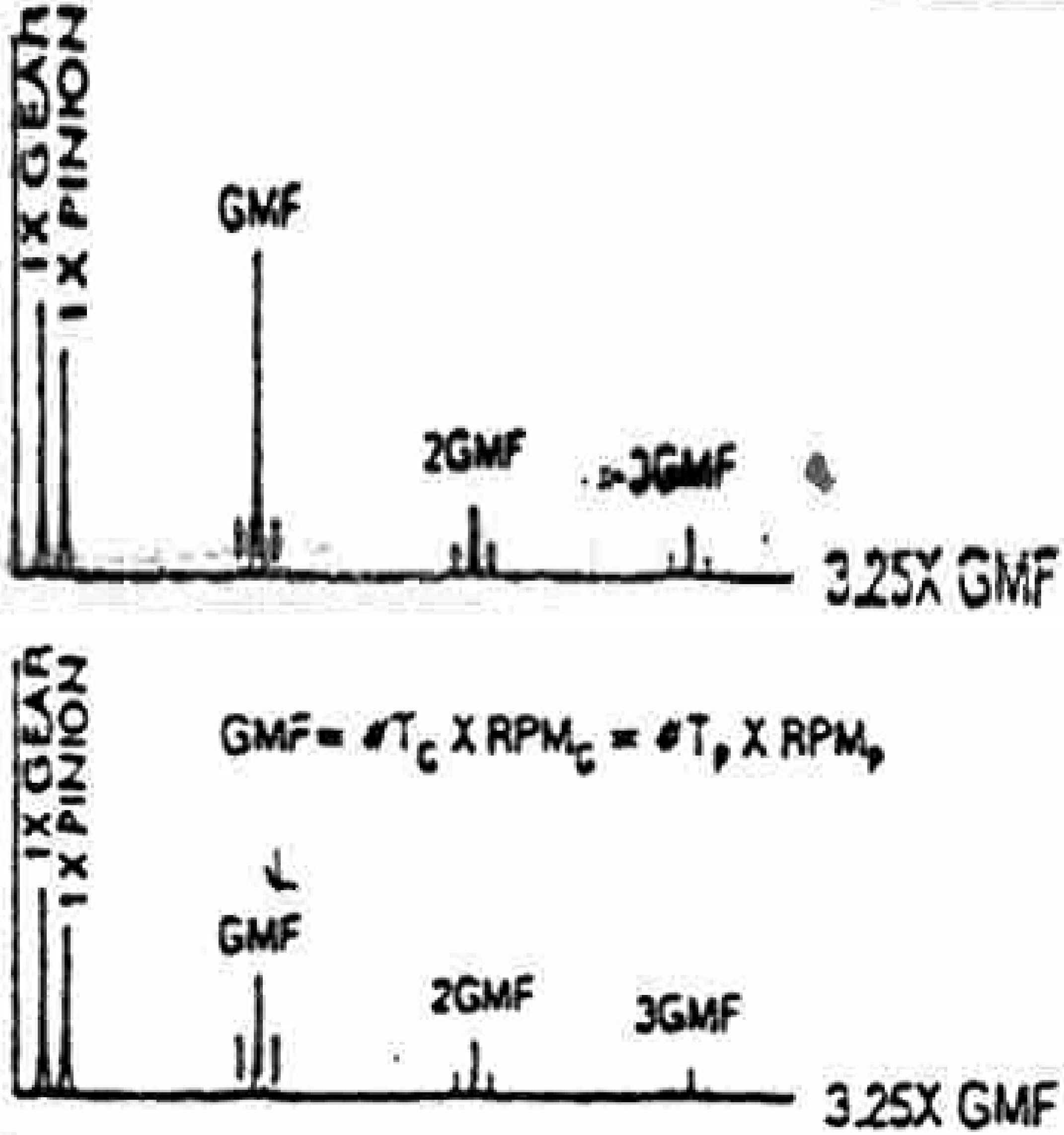
B. TOOTH WEAR


51T
26T


1X GEAR
1X PINION
Gear f_n
GEAR NATURAL FREQUENCY
GMF
2GMF
3GMF
3.25X GMF

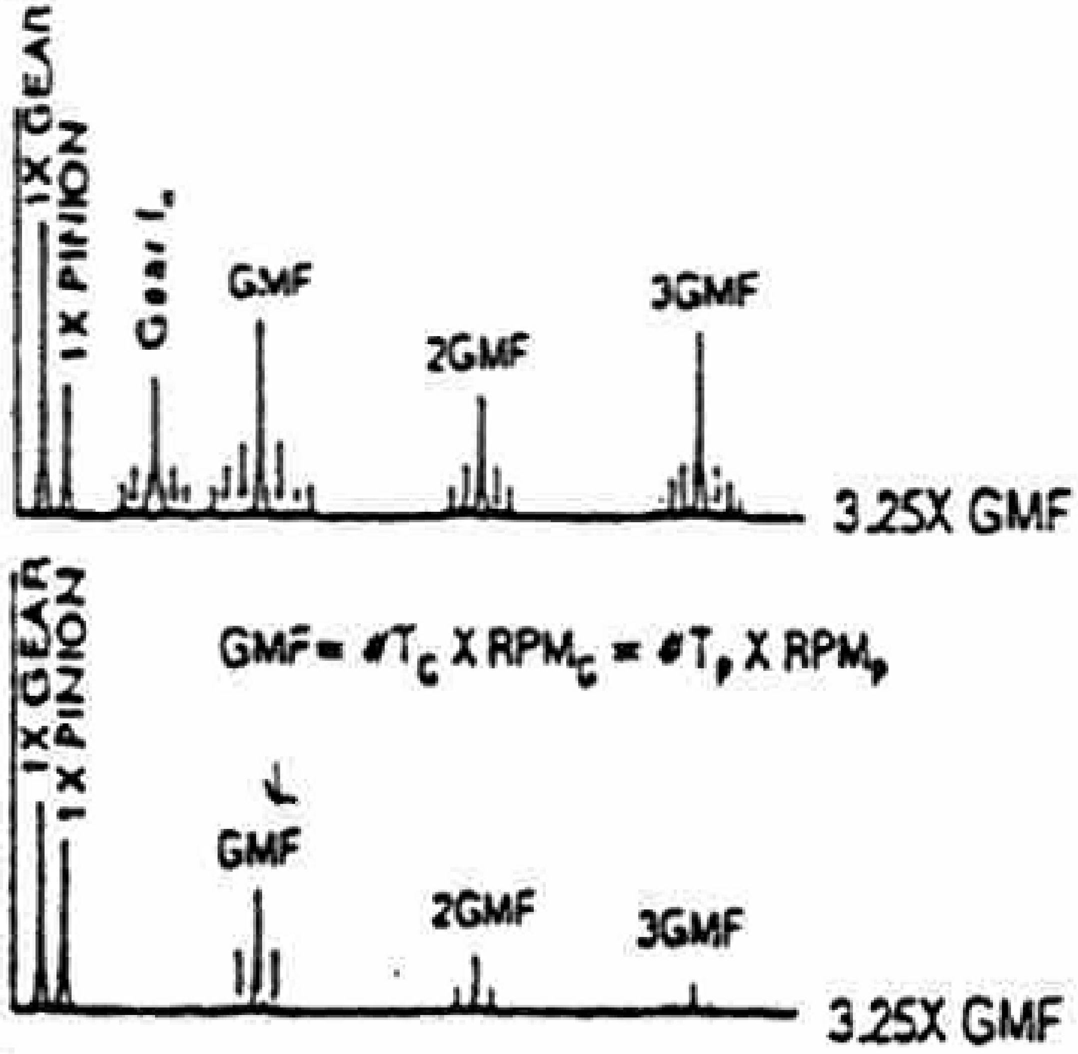

1X GEAR
1X PINION
GMF = $\#T_G$ X RPM_G = $\#T_P$ X RPM_P
GMF
2GMF
3GMF
3.25X GMF

C. TOOTH LOAD



1X GEAR
1X PINION
GMF
2GMF
3GMF
3.25X GMF
1X GEAR
1X PINION
GMF = #T_G X RPM_G = #T_P X RPM_P
GMF
2GMF
3GMF
3.25X GMF

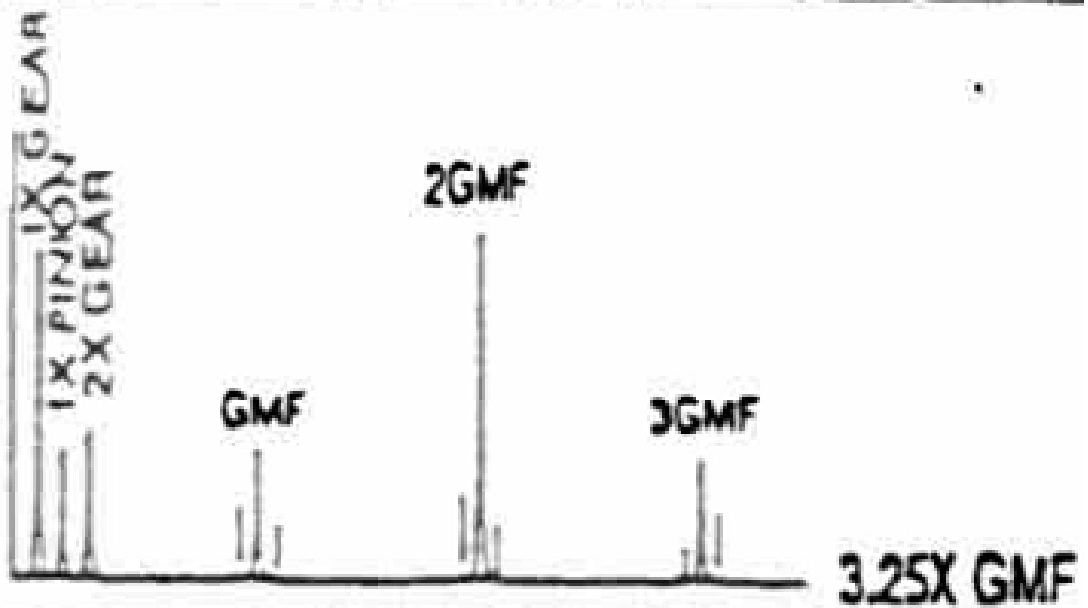
D. GEAR ECCENTRICITY AND BACKLASH

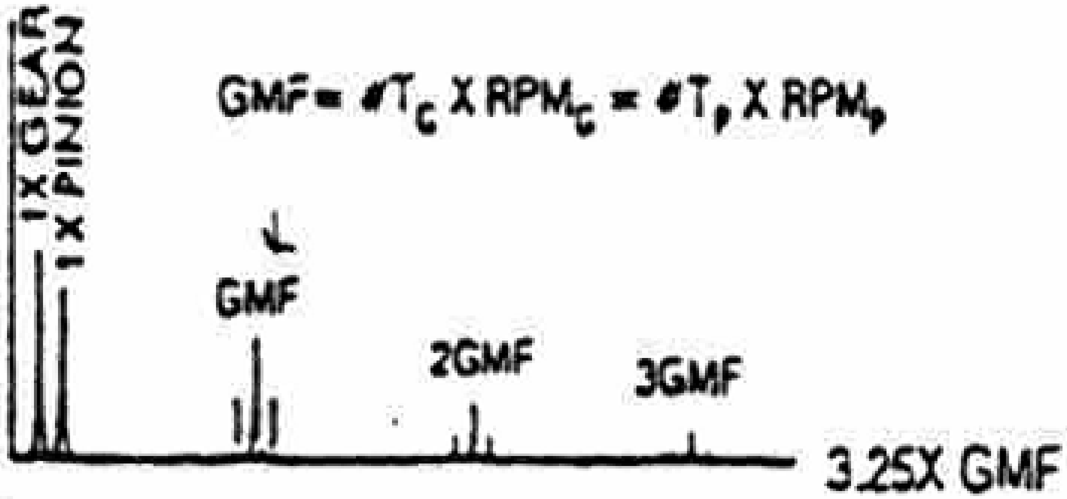


$GMF = \#T_G \times RPM_G = \#T_P \times RPM_P$

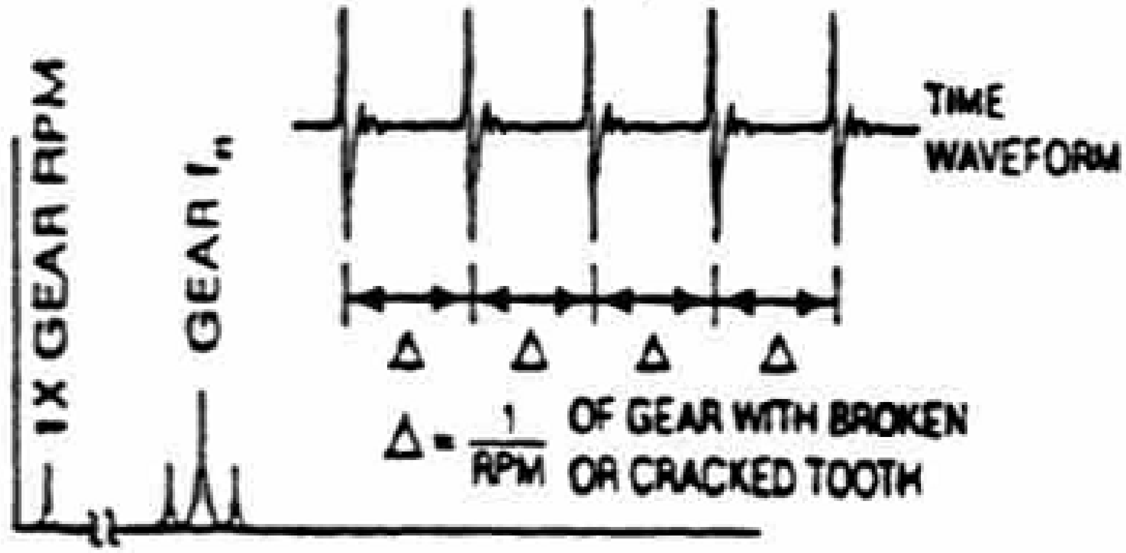
E. GEAR

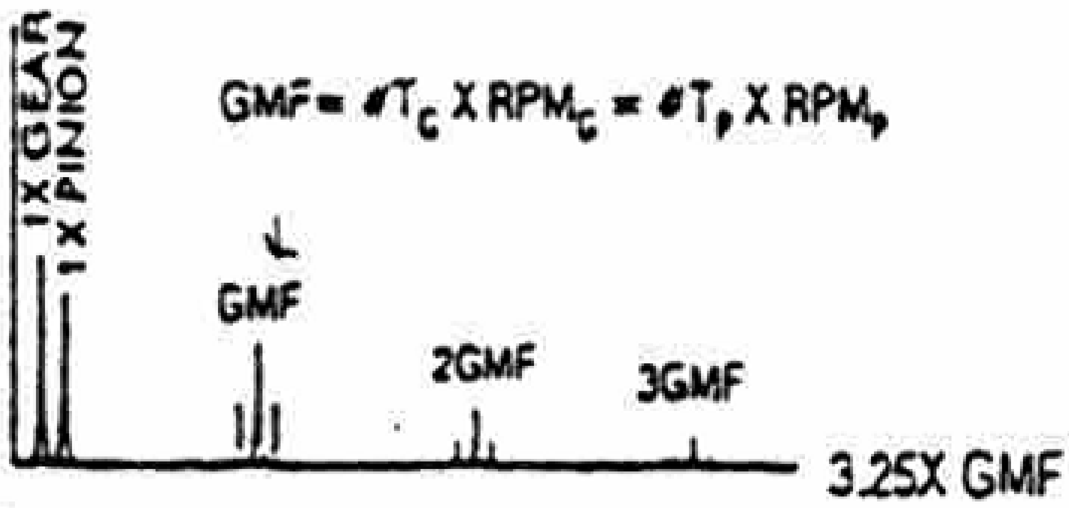
MISALIGNMENT



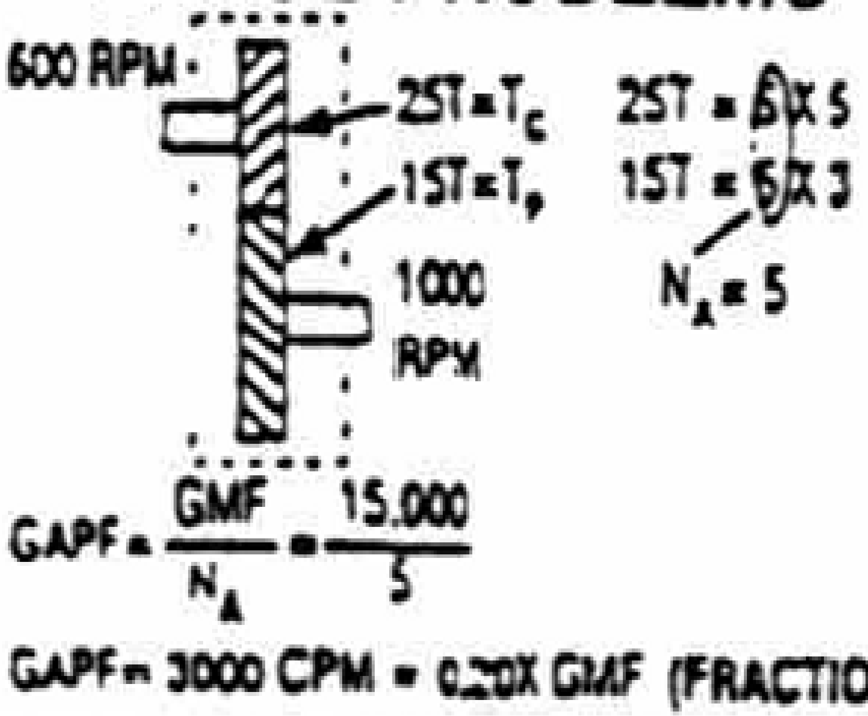


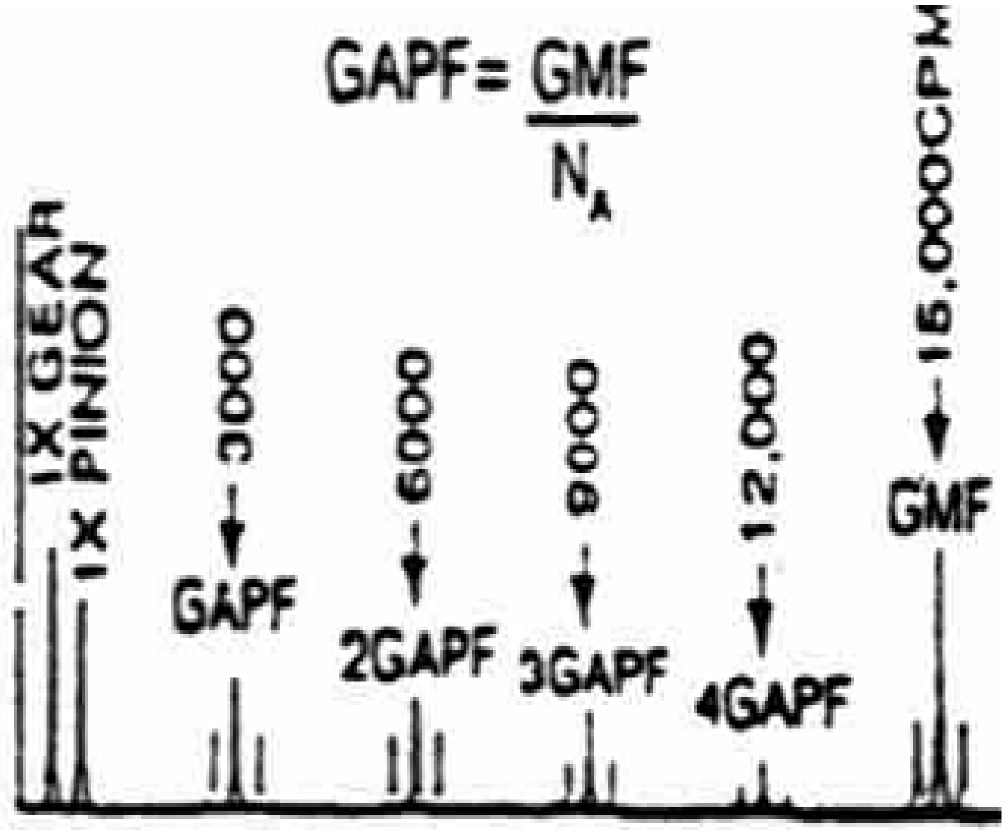
F. CRACKED/BROKEN TOOTH





G. GEAR ASSEMBLY PHASE PROBLEMS

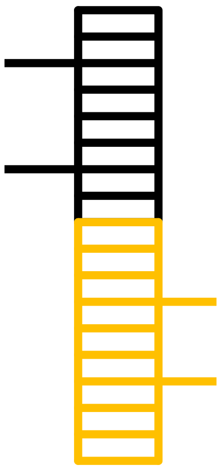




嚙合齒數之最大公因數效應

1×2×2×3

12齒



30齒

1×2×3×5

6

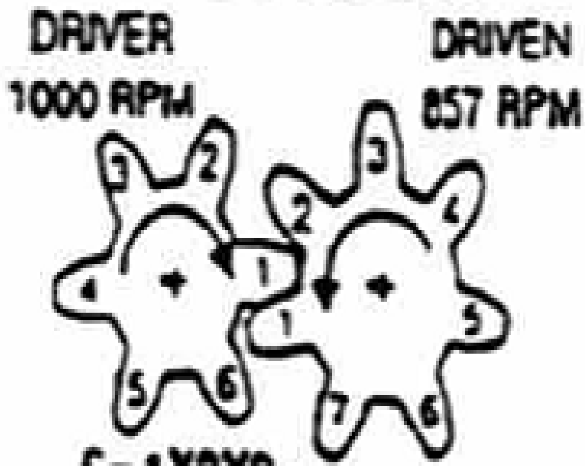
Common Factor	% of Life Expected
1	100%
2	50%
3	33%
4	25%
5	20%
6	16%
7	14%
8	12%
9	11%
10	10%

嚙合頻之分數倍頻

1/6, 2/6, 3/6, 4/6, 5/6,

1+1/6, 1+2/6, 1+3/6, 1+4/6, 1+5/6,

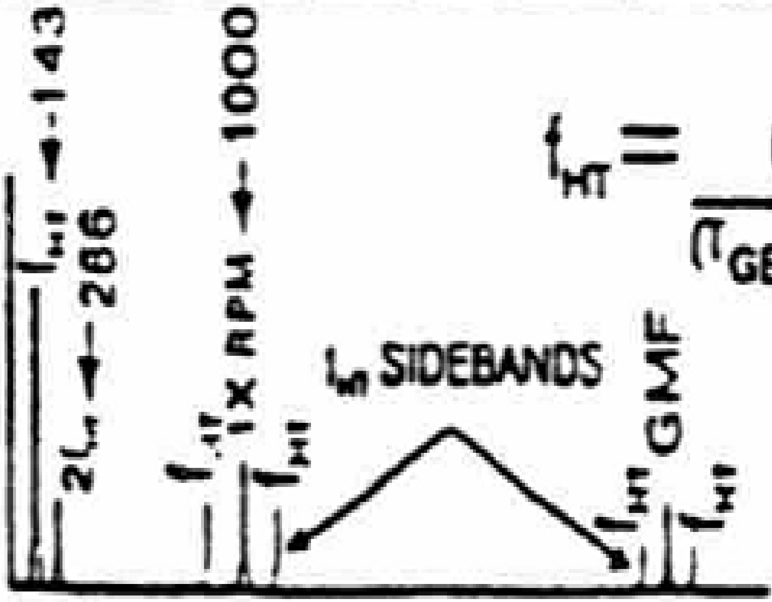
H. HUNTING TOOTH PROBLEMS



$6 = 1 \times 2 \times 3$

$7 = 1 \times 7$

$\} \; N_A = 1$



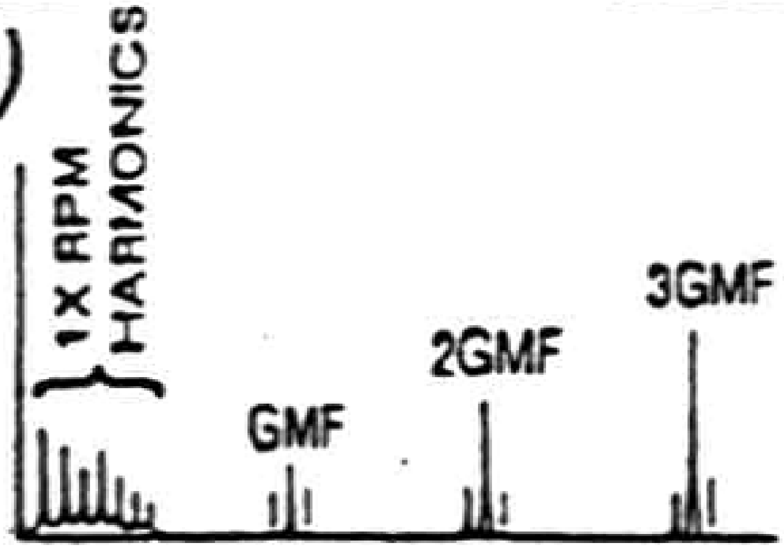
$$f_{HT} = \frac{(GMF)(N_A)}{(T_{GEAR})(T_{PINION})}$$

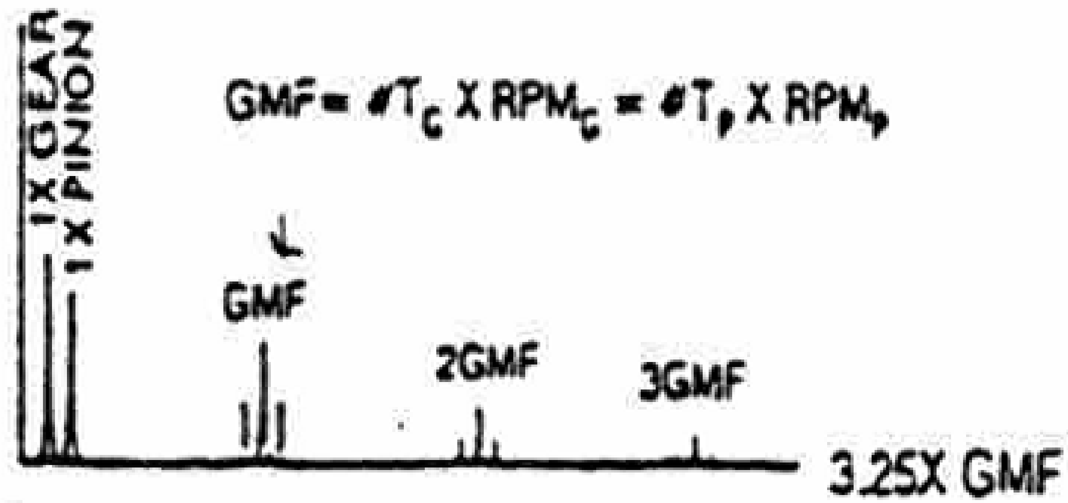
$N_A = 1$ is the ideal assembly phase factor in gear design

$$f_{HT} = \frac{(6 \times 1000)(1)}{(6)(7)} = \frac{1000}{7} = 143 \text{ CPM (One Pulse Per 7 Pinion Revolutions)}$$

GEARS (CONTINUED)

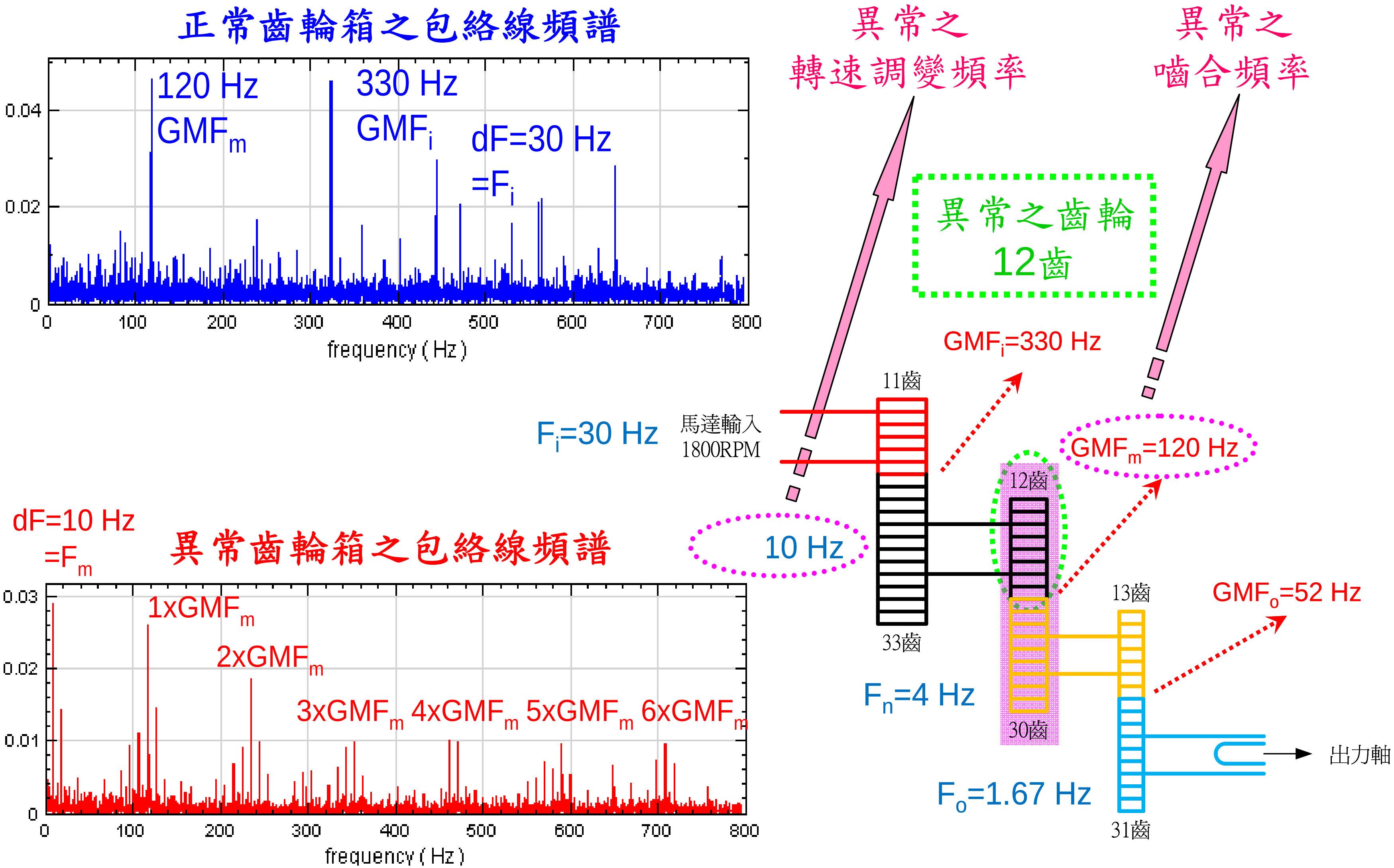
I. LOOSE BEARING FIT





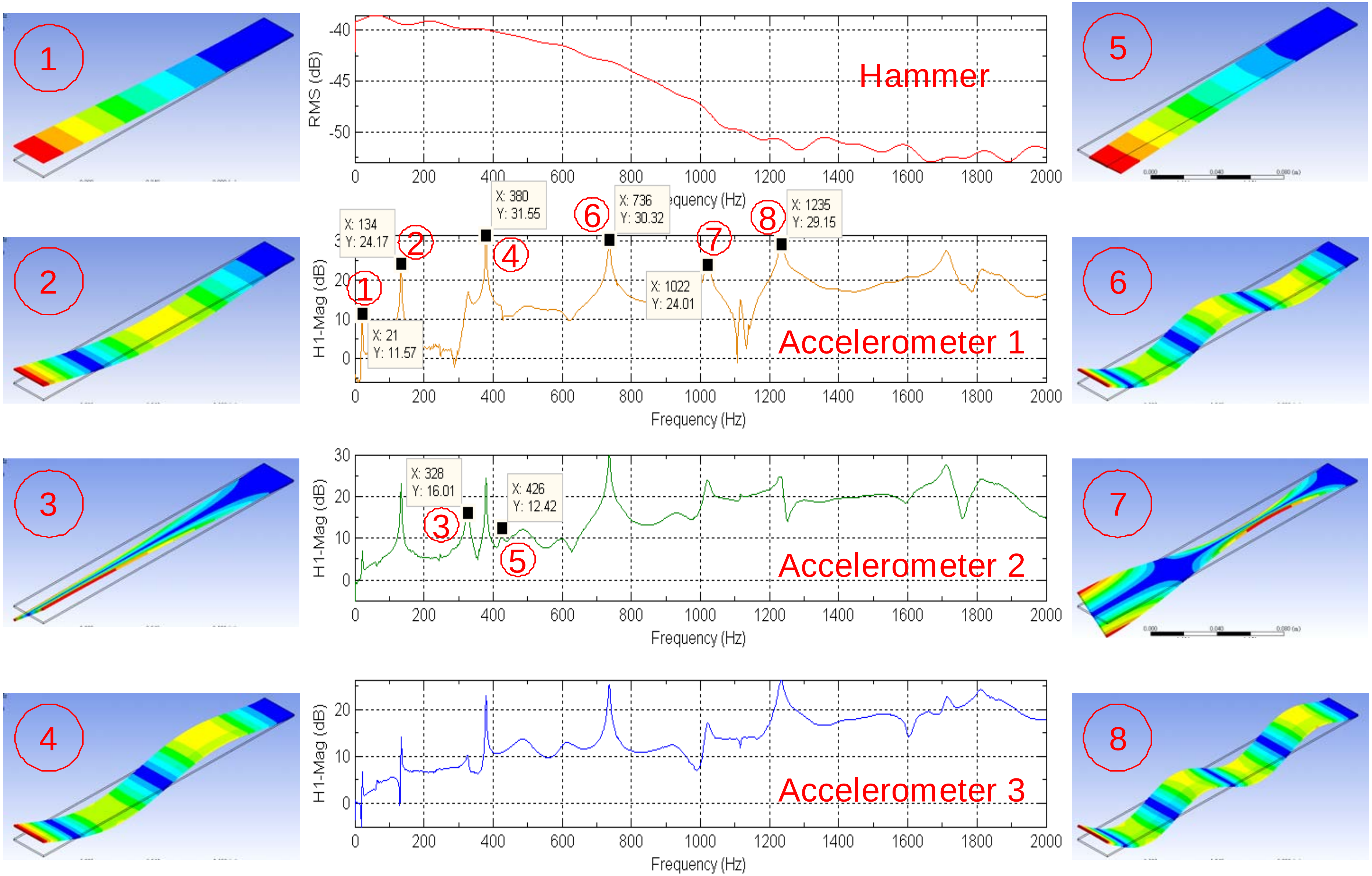
變速齒輪箱之嚙合異常檢測

偏心、對心、鬆脫、背隙、磨損、斷齒



結構之自然頻率檢測

利用敲擊測試之自然頻率驗證有限元素分析之正確性



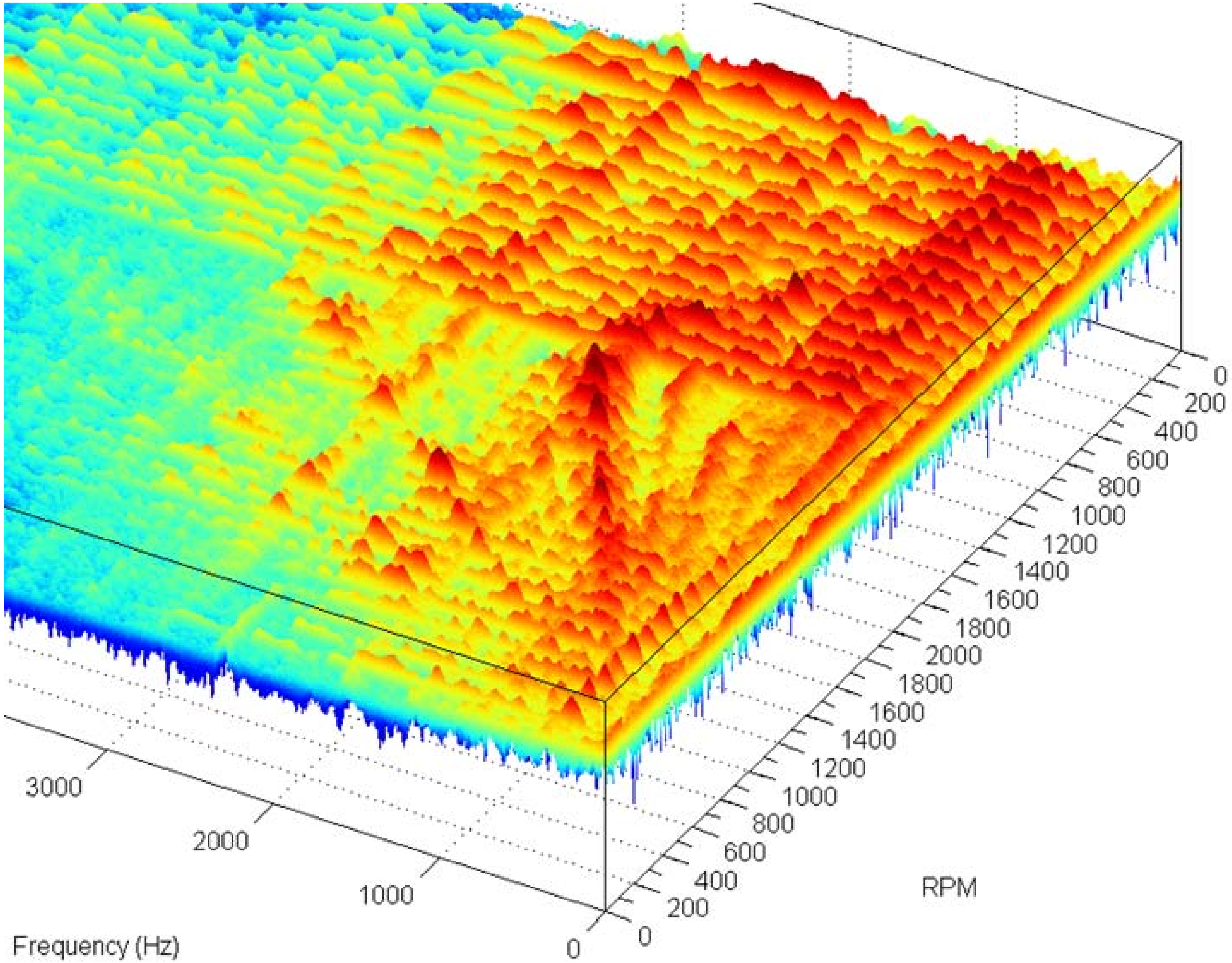
懸臂樑：量測頻率與模擬結果比較→修正數值模型

Mode	量測頻率	原始分析	差異 %	修正分析	差異 %
1	21 Hz	23.071 Hz	**9.8619**	21.467 Hz	2.2238
2	134 Hz	144.5 Hz	**7.8358**	134.46 Hz	0.3433
3	328 Hz	367.6 Hz	**12.073**	347.76 Hz	6.0244
4	380 Hz	404.91 Hz	**6.5553**	376.78 Hz	-0.8474
5	426 Hz	459.16 Hz	**7.7840**	442.13 Hz	3.7864
6	736 Hz	794.75 Hz	**7.9823**	739.54 Hz	0.4810
7	1022 Hz	1111.4 Hz	**8.7476**	1051.2 Hz	2.8571
8	1235 Hz	1316.4 Hz	**6.5911**	1225.0 Hz	-0.8097

變轉速時頻分析：轉速倍頻與自然頻率之確認

隨轉速變化：
轉速頻率之倍頻
(嚙合頻)

不隨轉速變化：
共振(自然頻率)
背景噪音/干擾

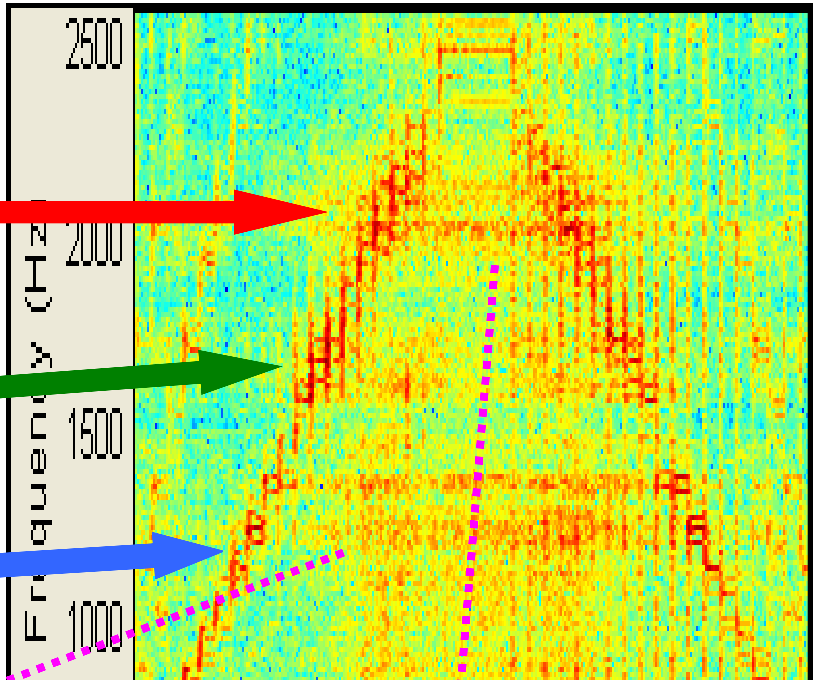


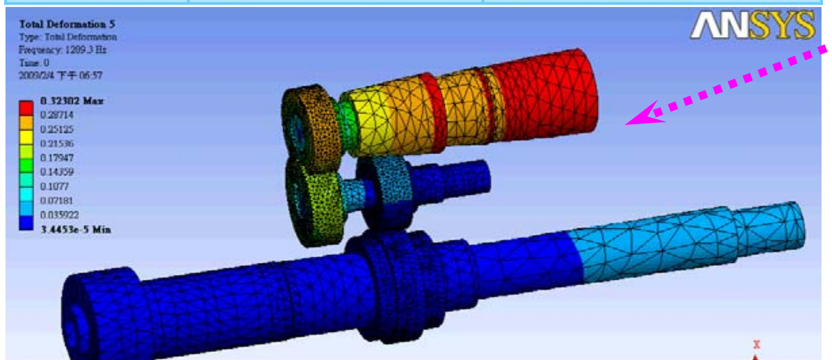
結構之自然頻率檢測
利用變轉速時頻驗證有限元素分析之正確性

FEM模擬結果：

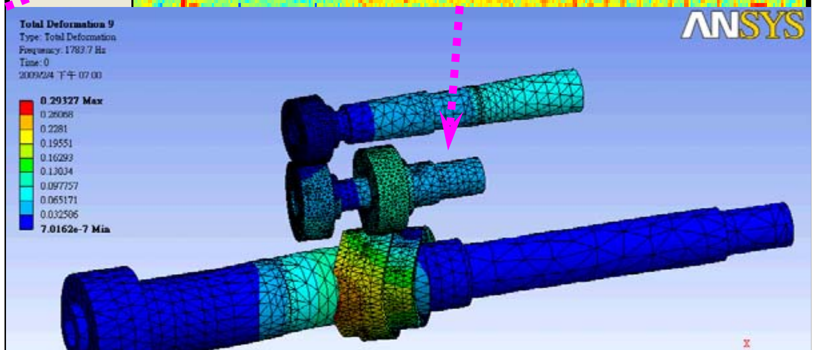
模態	模態形式	自然頻率 (Hz)
12	Coupling	2289
11	Coupling	2176
10	Coupling	2003
9	Coupling	1784
8	Torsion	1541
7	Bending	1421
6	Bending	1415
5	Torsion	1289

量測結果：



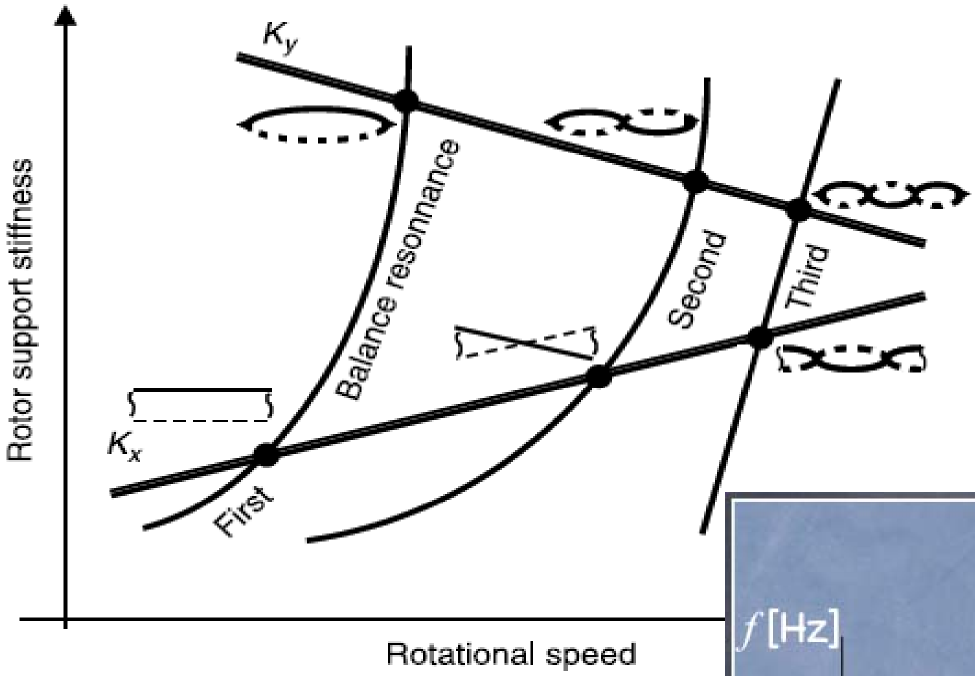


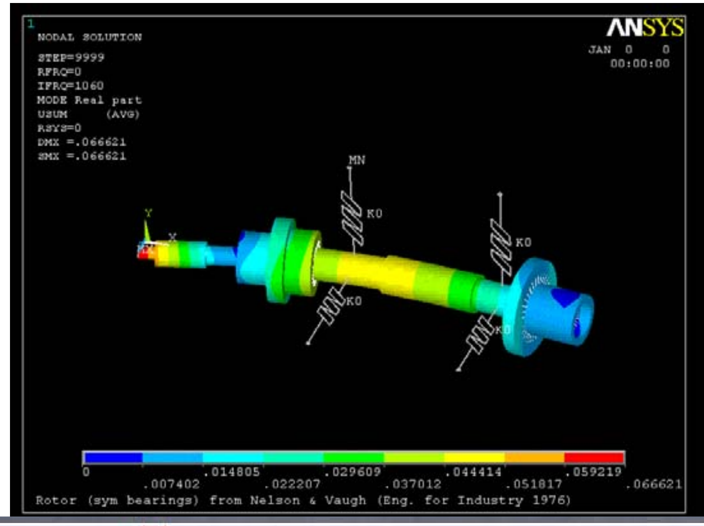
5th mode 扭轉模態

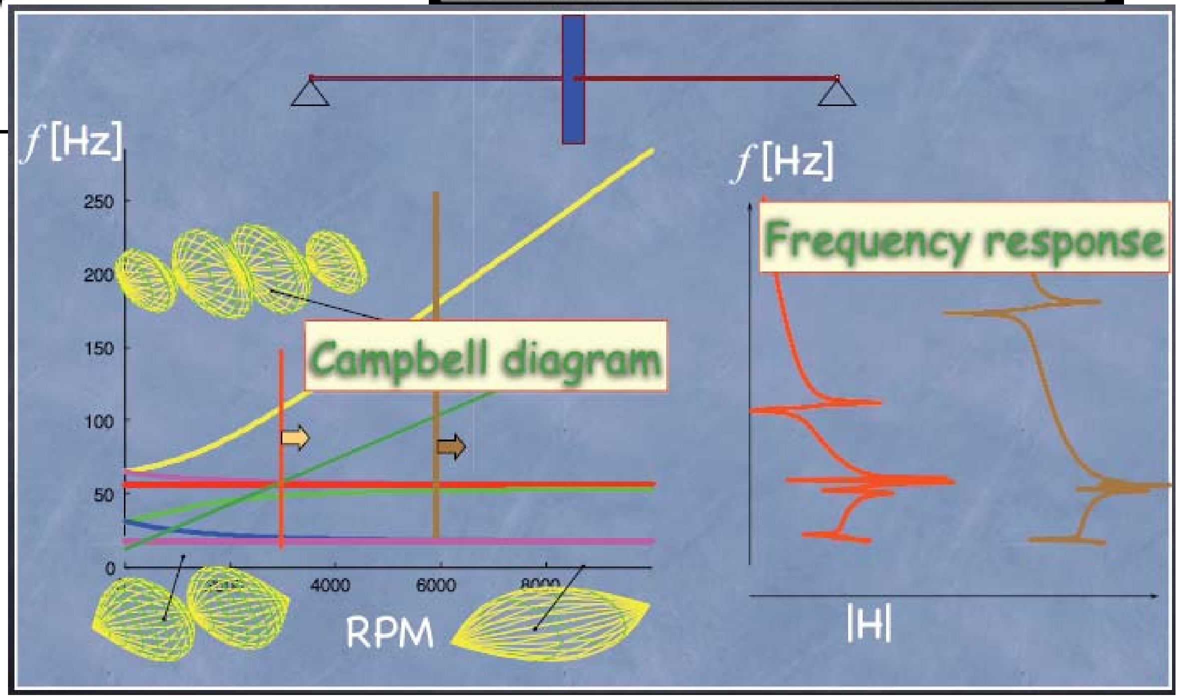


9th mode 耦合模態

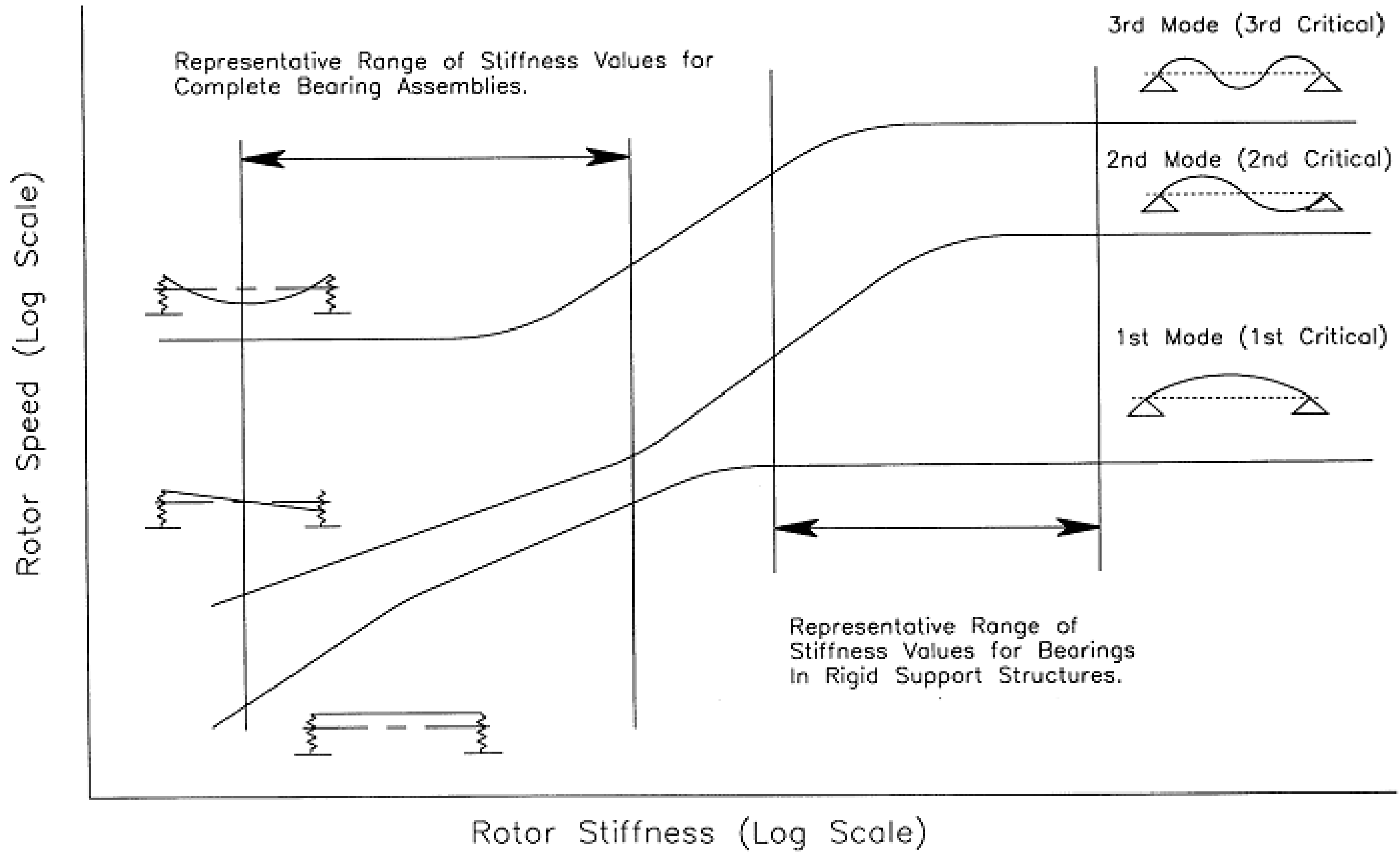
軸承剛性與主軸臨界轉速之關係



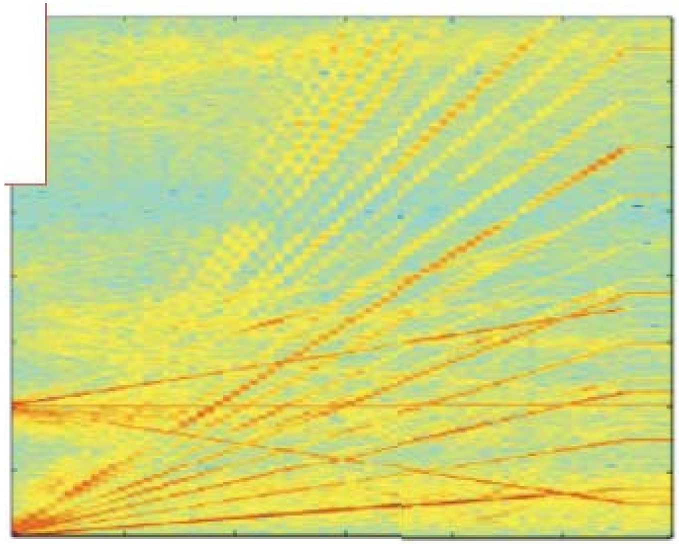


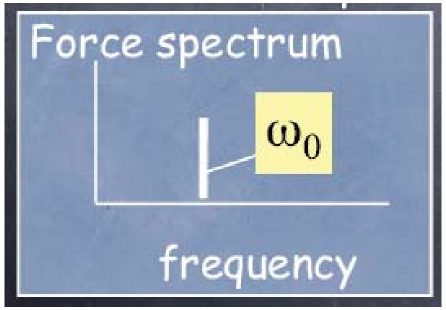


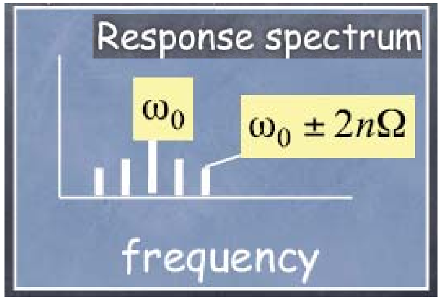
軸承剛性之影響

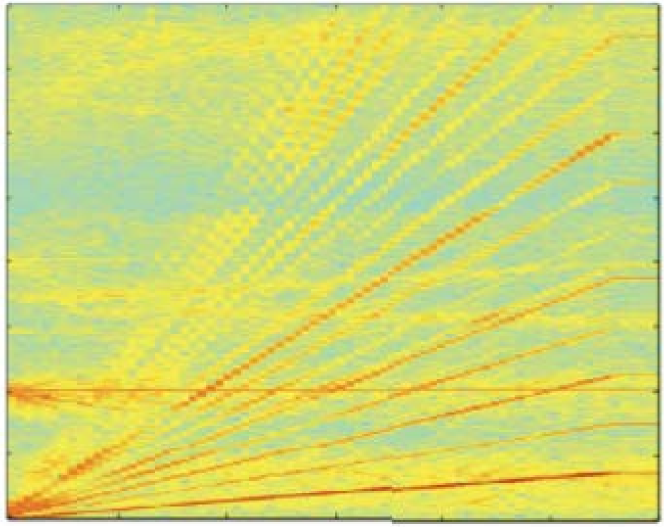

3rd Mode (3rd Critical)
Representative Range of Stiffness Values for Complete Bearing Assemblies.
2nd Mode (2nd Critical)
1st Mode (1st Critical)
Rotor Speed (Log Scale)
Representative Range of Stiffness Values for Bearings In Rigid Support Structures.
Rotor Stiffness (Log Scale)

異常調變排除⇨主軸非對稱效應之校平衡

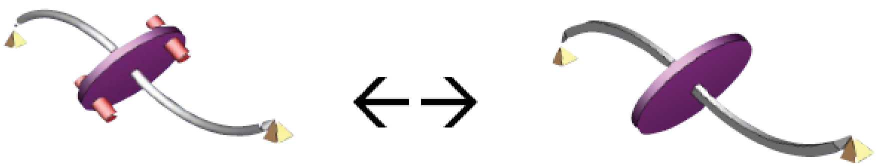








Asymmetric inertia ←→ anisotropic stiffness

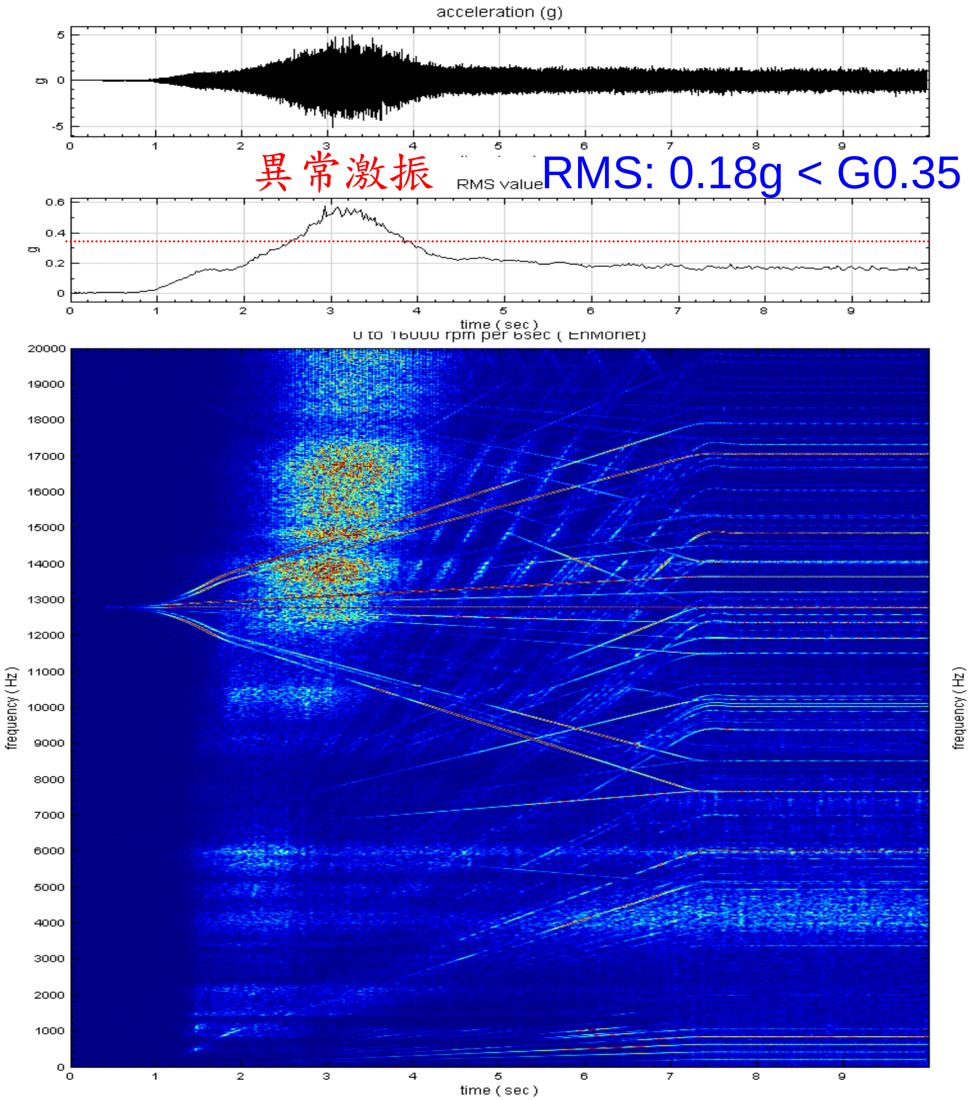


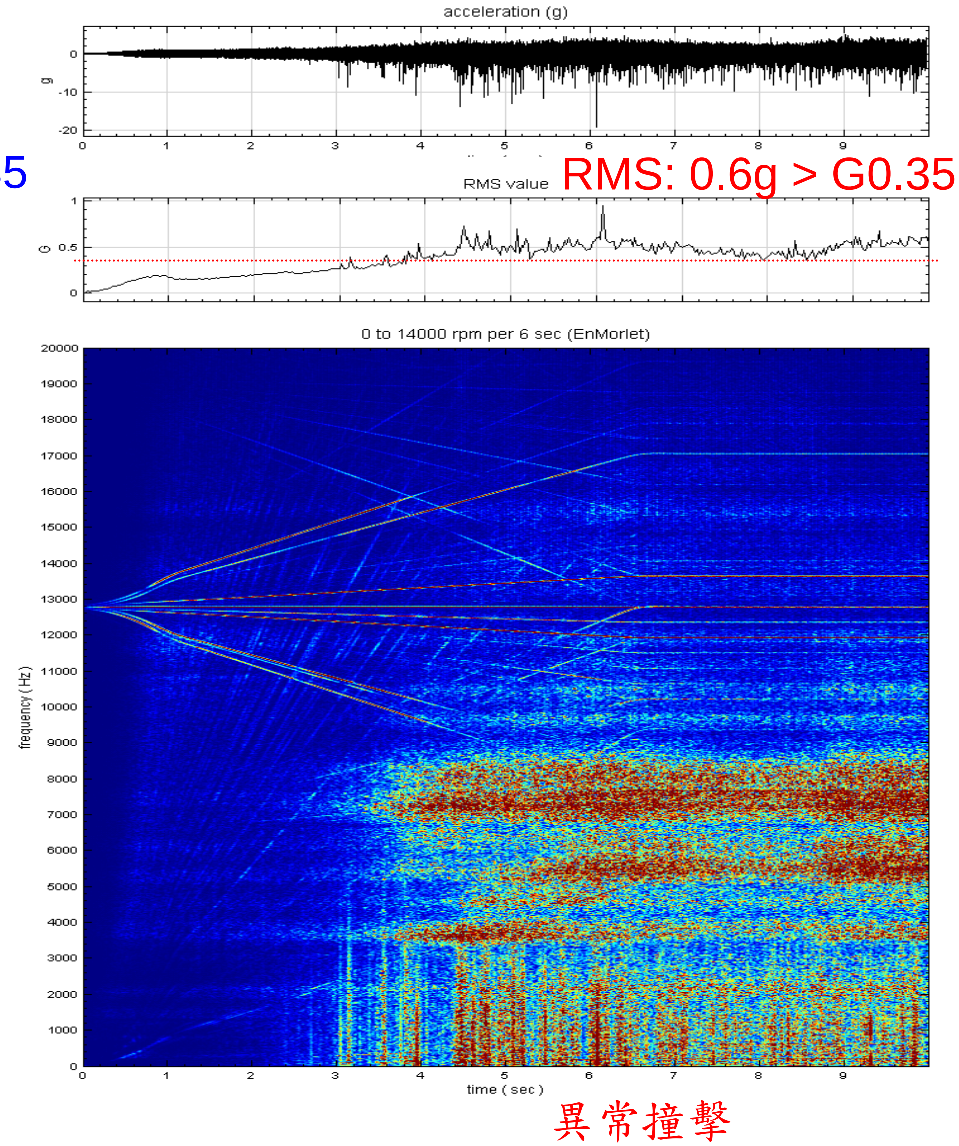
* for asynchronous detection purposes

- Force frequency ω
- Speed of rotation Ω
- Response frequencies ω, $\omega \pm 2n\Omega$
- Resonance frequencies ω, $\omega \pm n\Omega$

Why變轉速時頻分析?

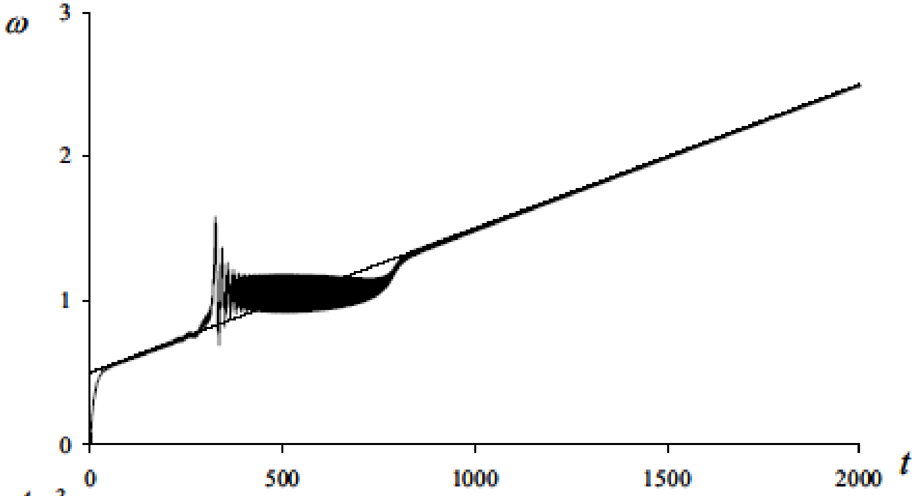
⇨轉速倍頻、共振頻段、異常激振、頻率調變

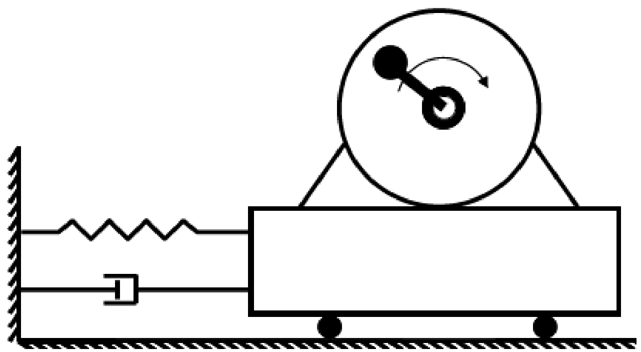


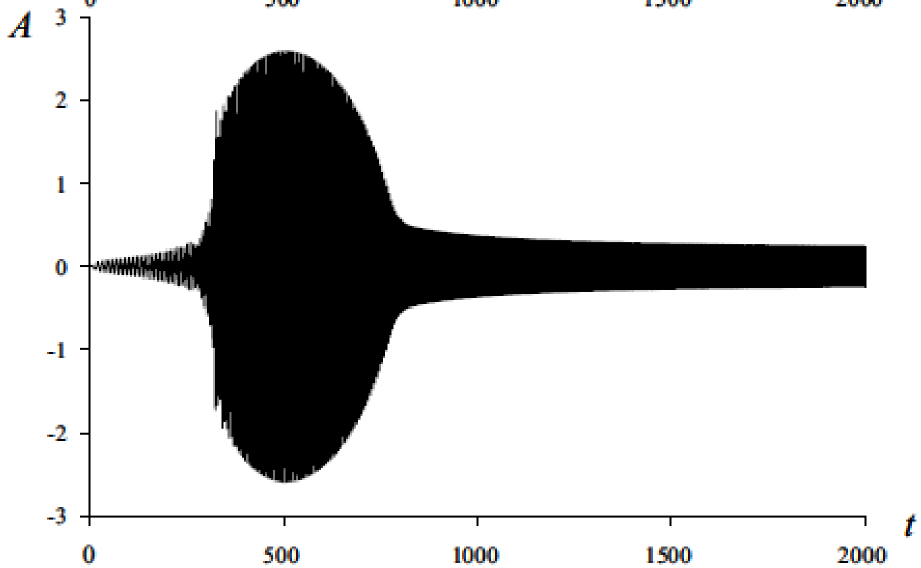


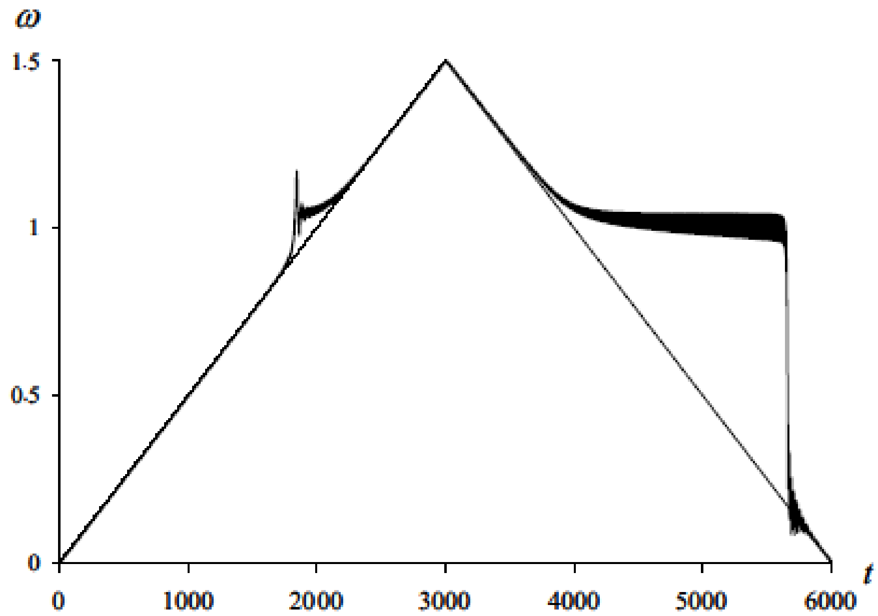
臨界轉速&共振頻率

非線性振動：暫態效應、鎖定共振

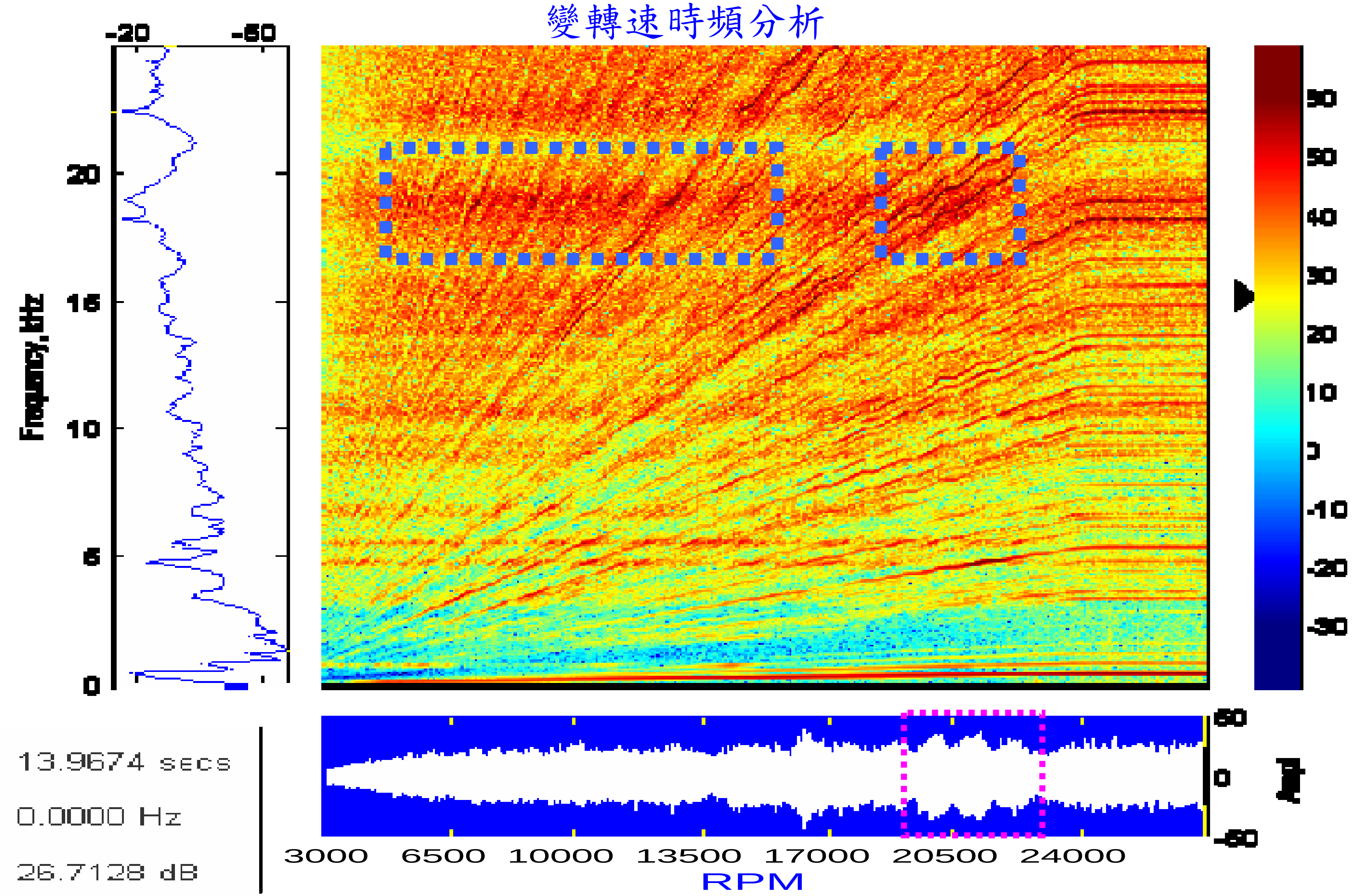




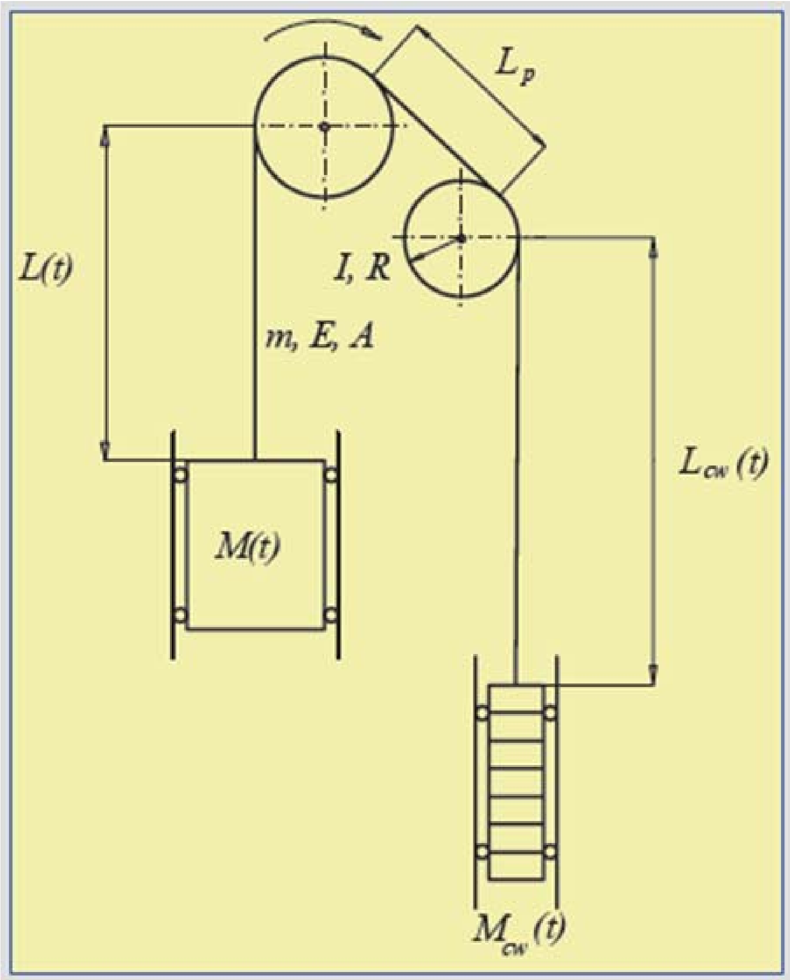




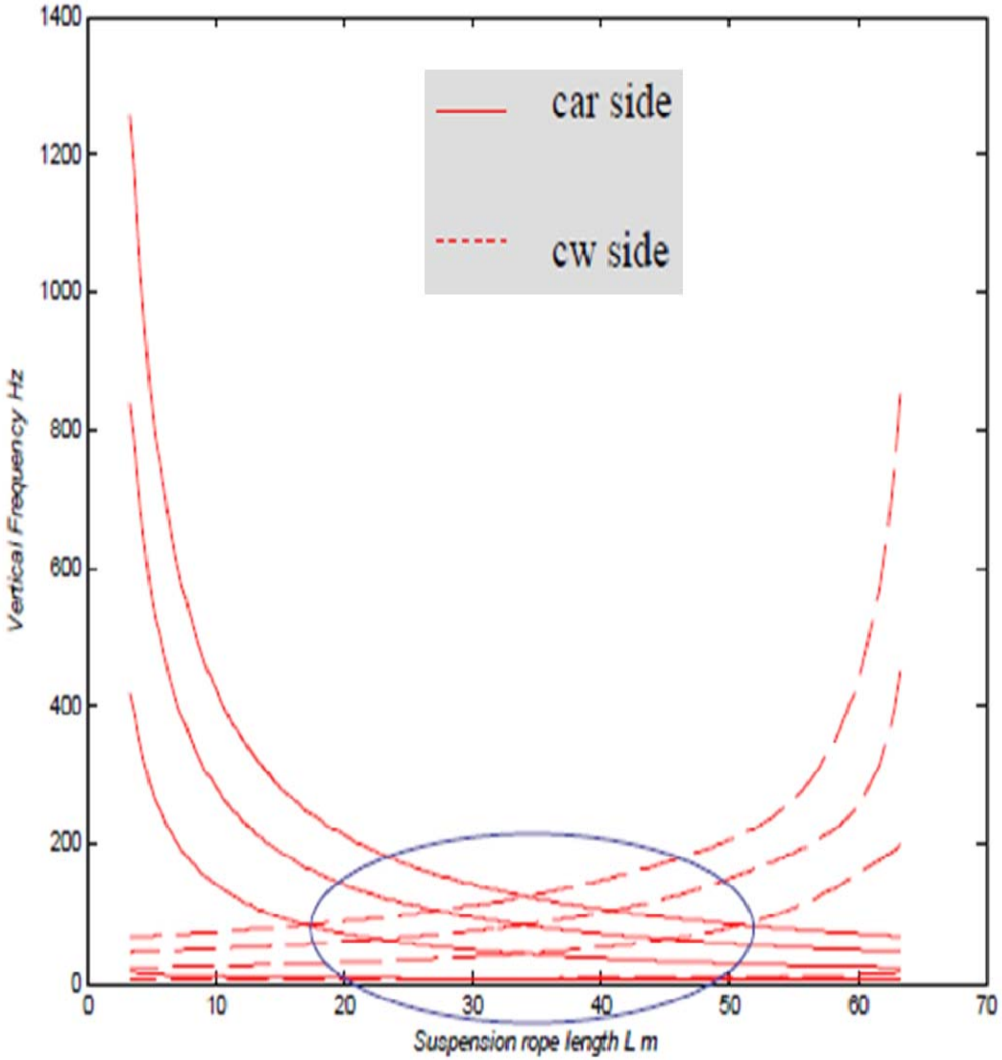
變轉速時頻分析：臨界轉速



電梯系統自然頻率



L_p
$L(t)$
I, R
m, E, A
$L_{cw}(t)$
$M(t)$
$M_{cw}(t)$



car side
cw side
Vertical Frequency Hz
Suspension rope length L m
0
200
400
600
800
1000
1200
1400
10
20
30
40
50
60
70

電梯系統振動時頻分析