

# 時頻分析於迴轉機械之振噪檢測

吳豐泰

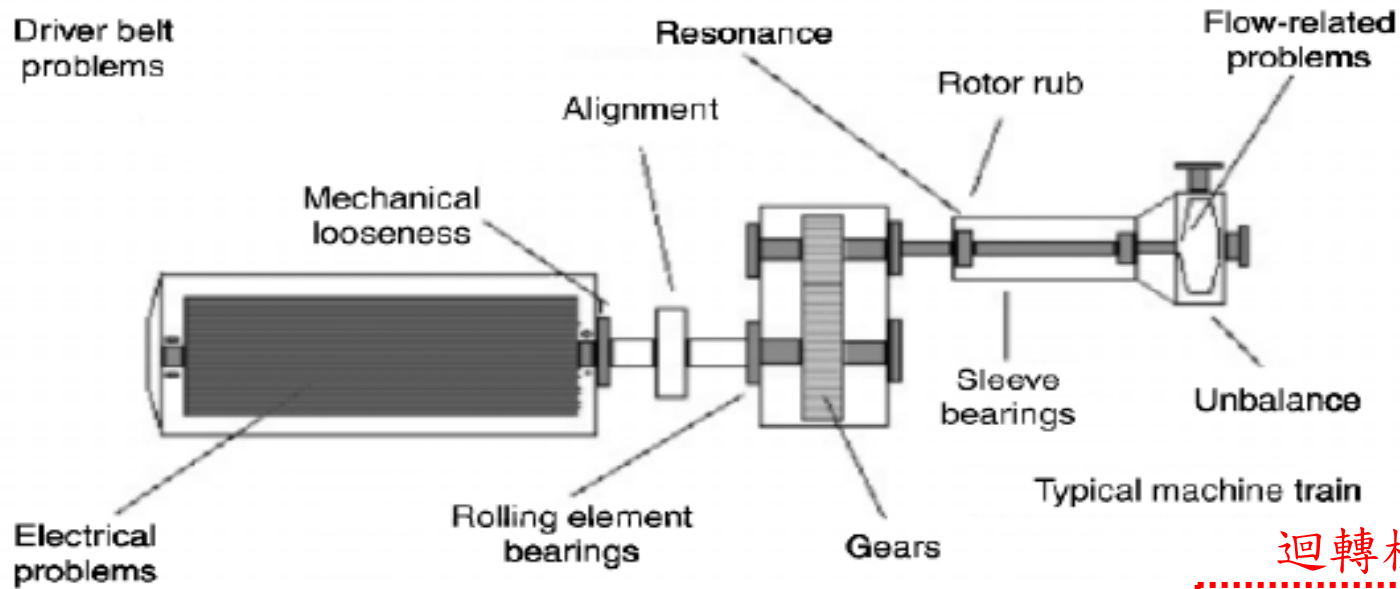
逸奇科技



# 迴轉機械之振動頻譜

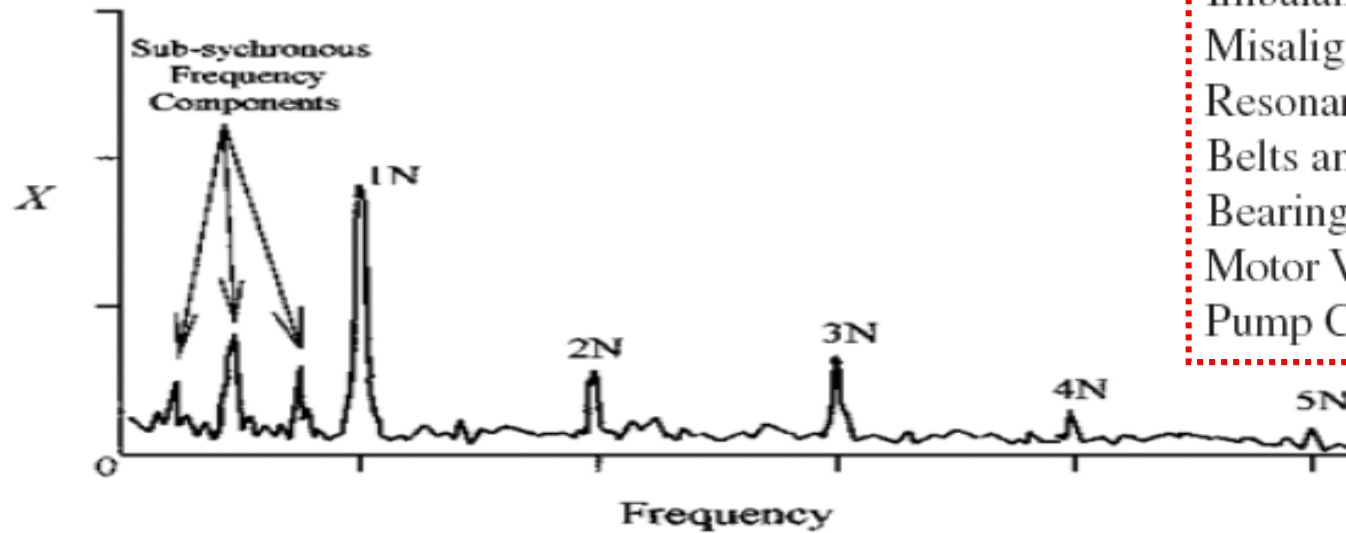


# 迴轉機械之傳動與典型振動頻譜



## 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%

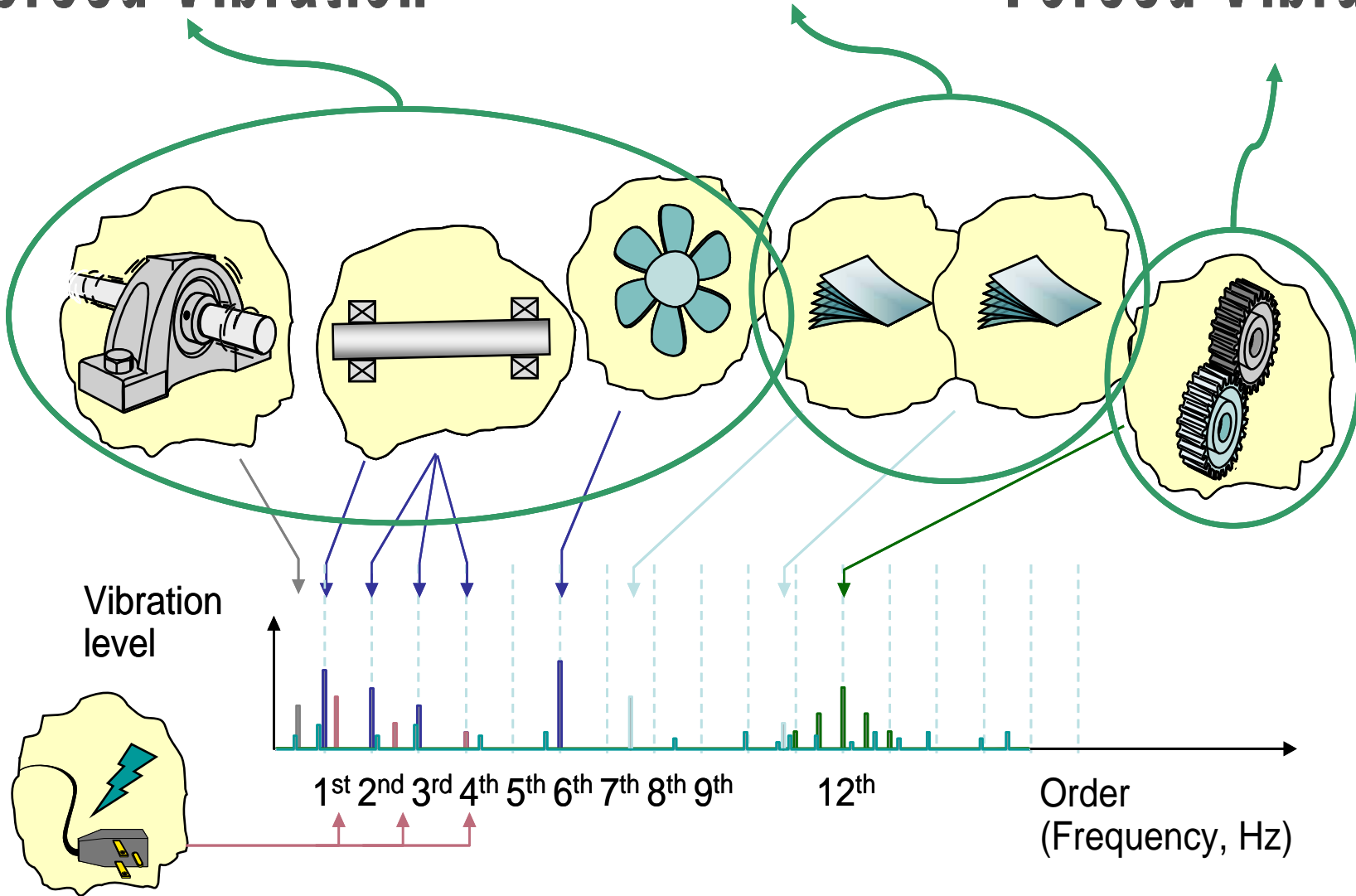


# 迴轉機械之轉速倍頻振動頻譜

Forced Vibration

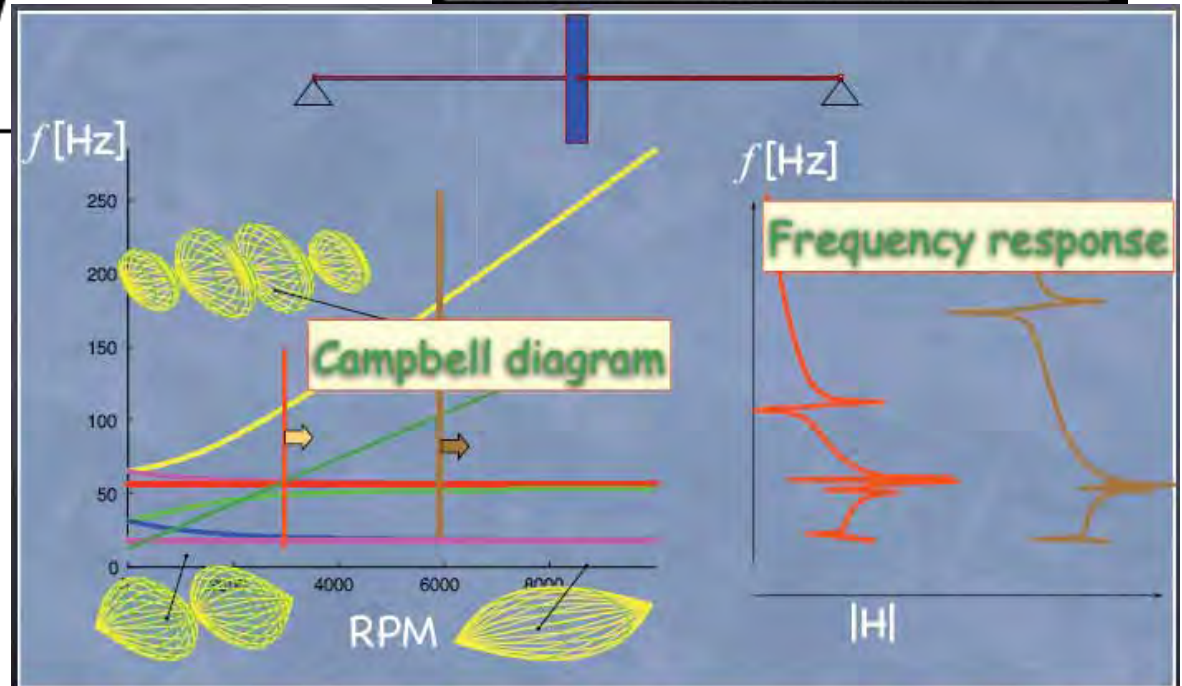
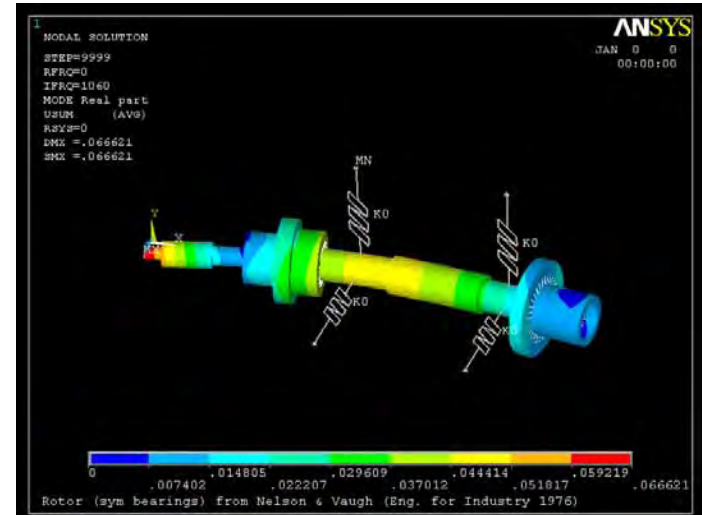
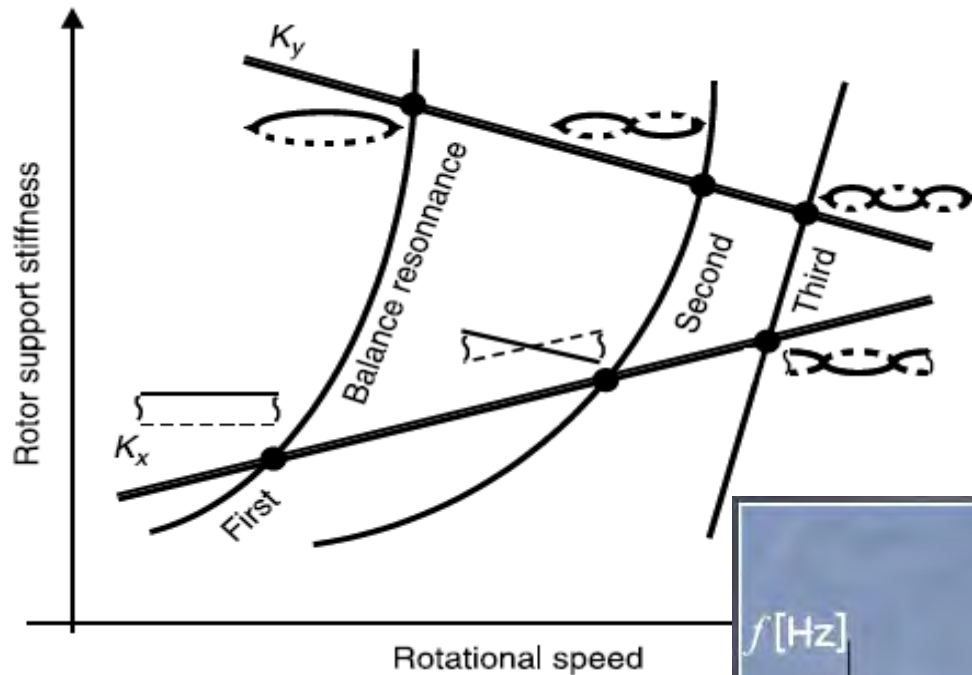
Resonance

Forced Vibration

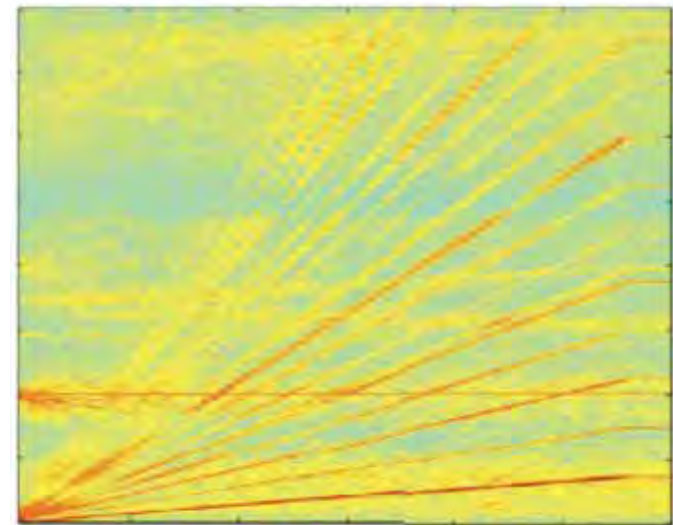
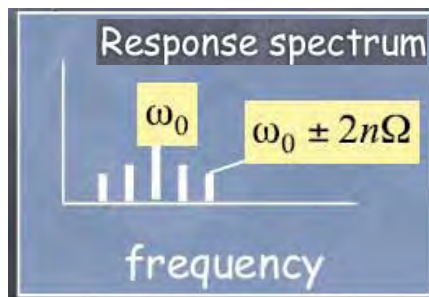
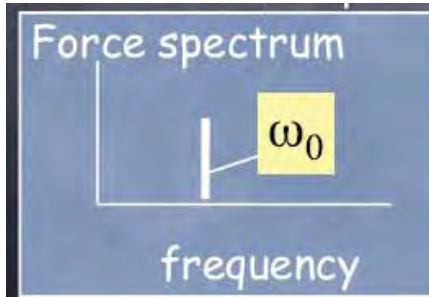
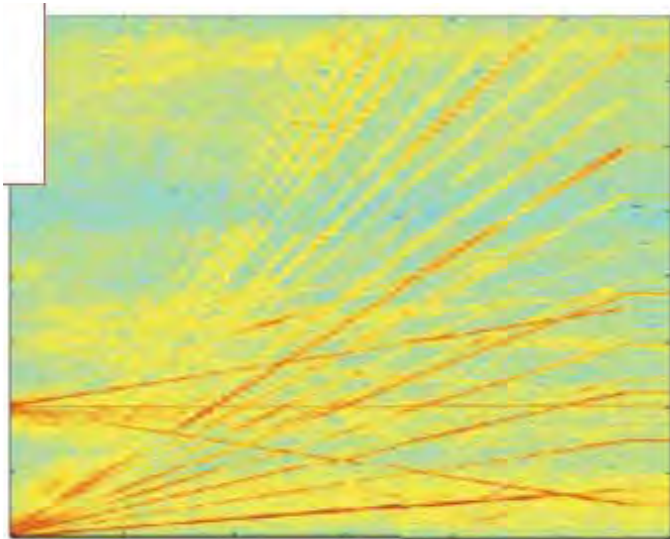




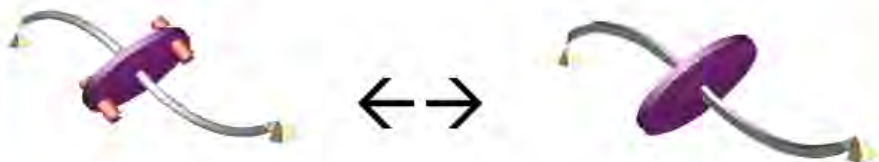
# 軸承剛性與主軸臨界轉速之關係



# 異常調變排除 $\Rightarrow$ 主軸非對稱效應之校平衡



Asymmetric inertia  $\leftrightarrow$  anisotropic stiffness



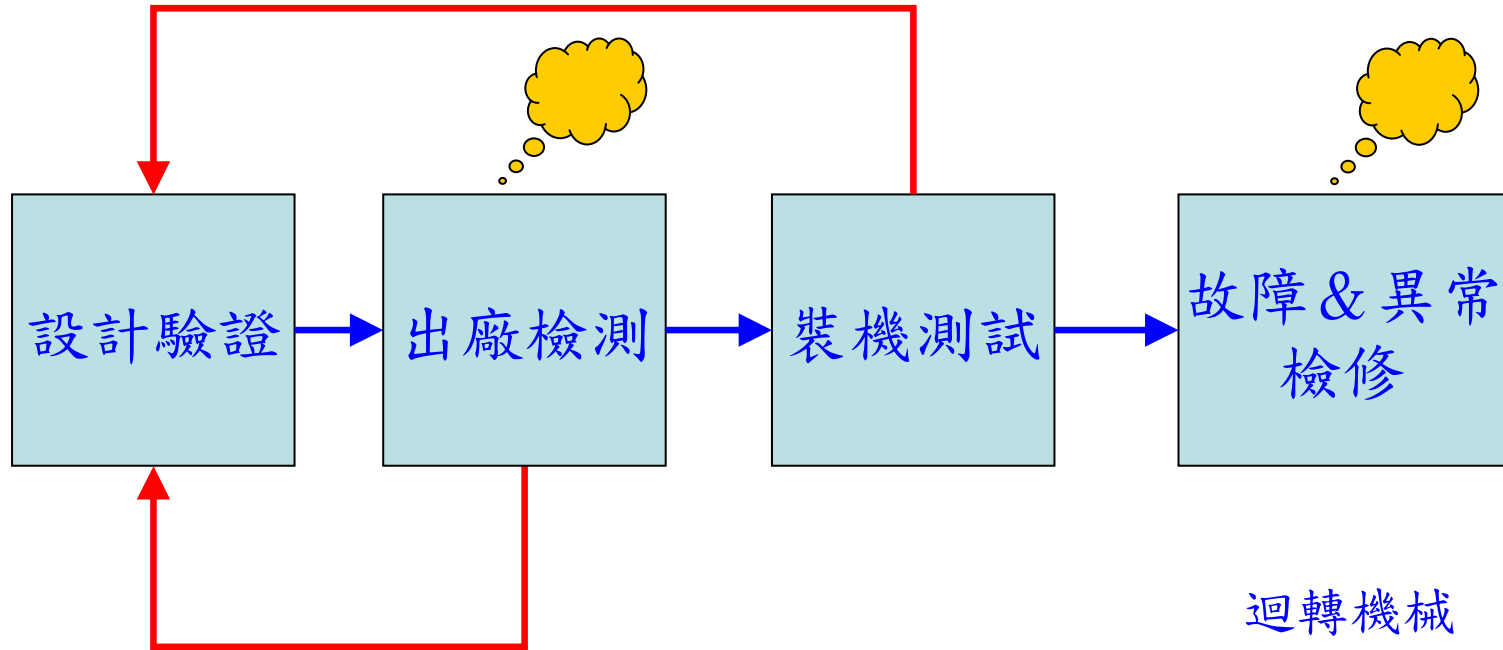
\* for asynchronous detection purposes

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



# PC-based 檢測系統

# Why 振動噪音檢測？



FEM模型  
原型驗證  
參數調測

生產履歷：  
製造&組裝  
品保資料庫  
臨界轉速

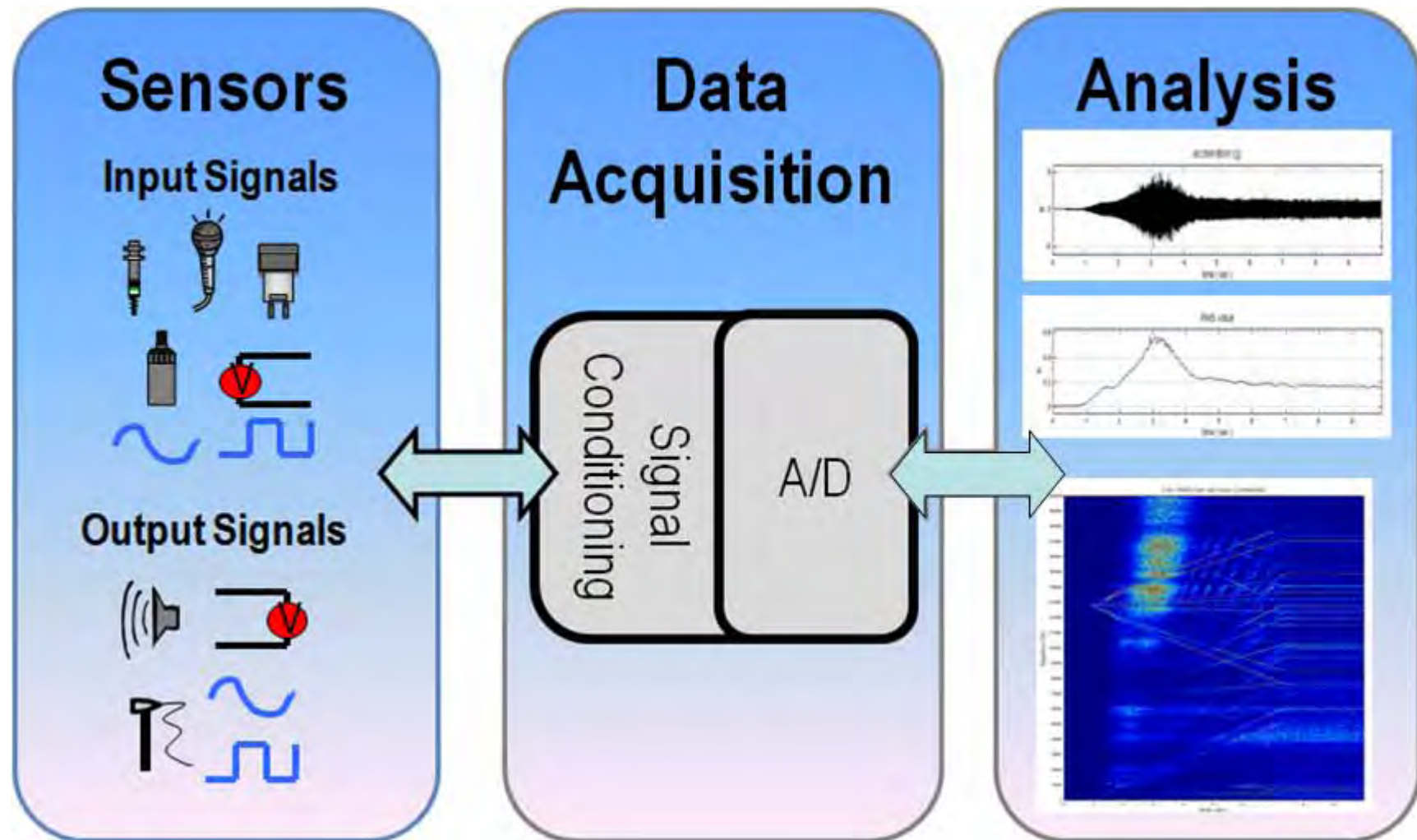
客戶機台  
動態特性  
操作頻率  
臨界轉速

迴轉機械

主軸  
齒輪  
軸承  
馬達



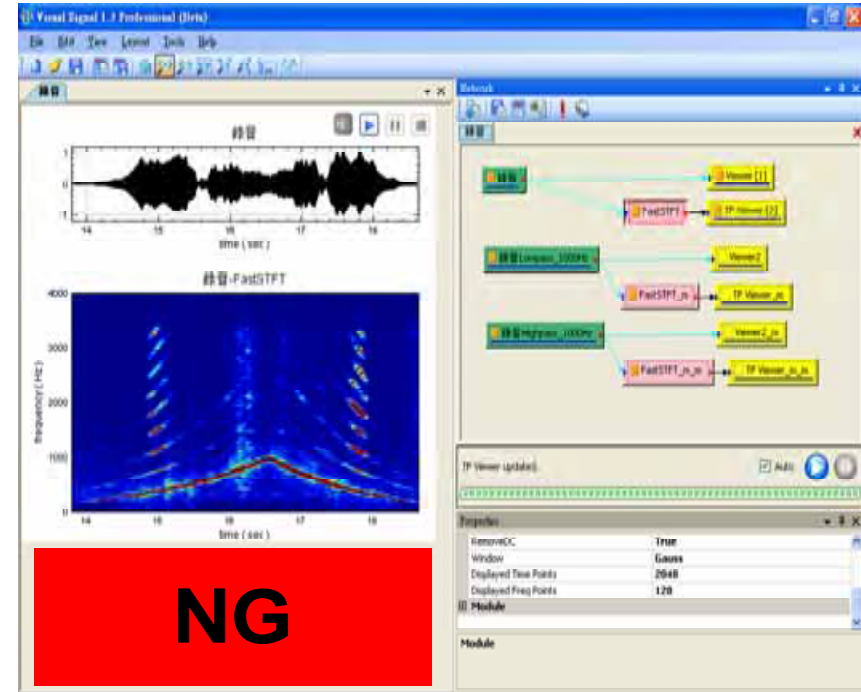
# PC-based 檢測流程



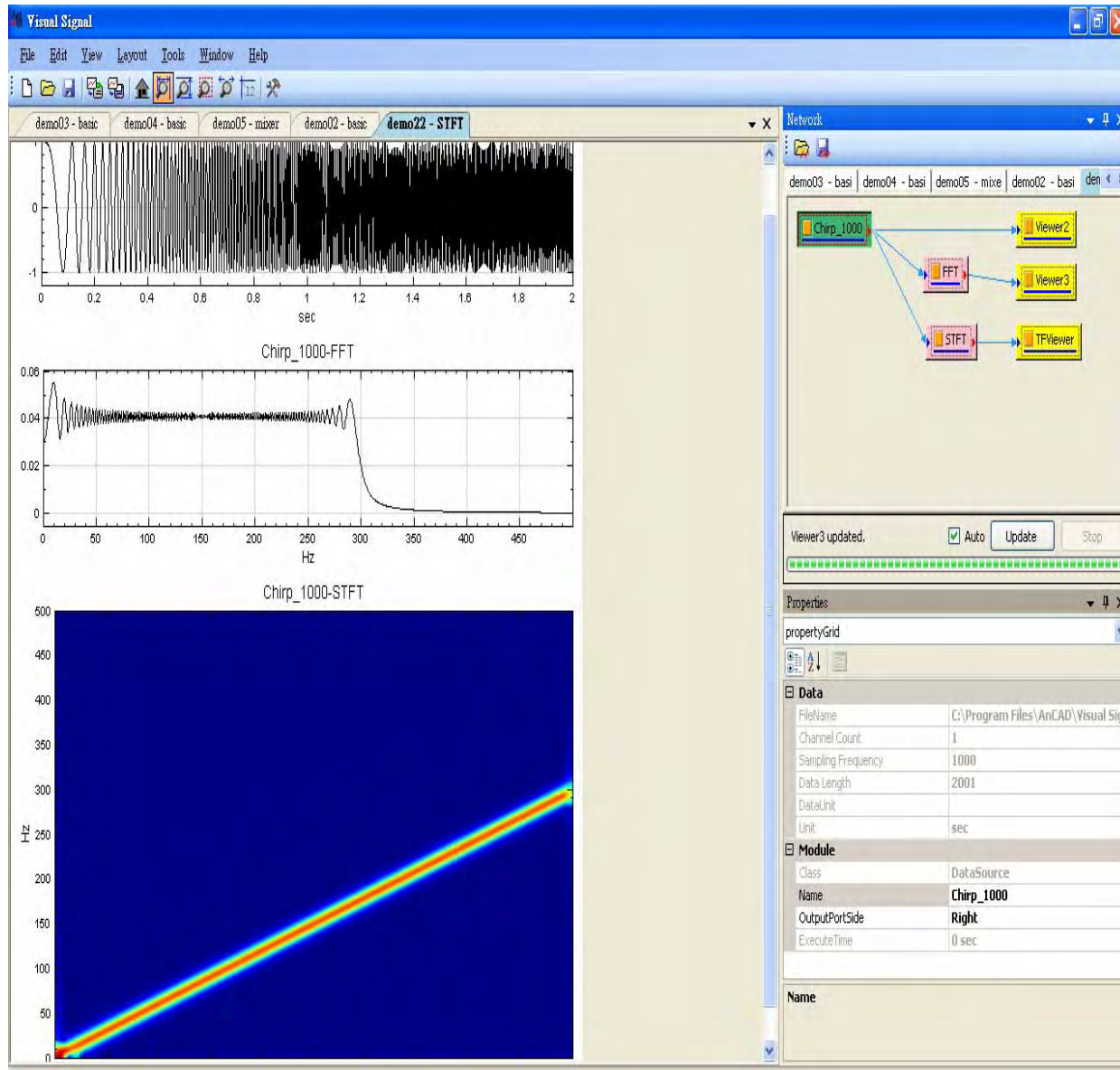
# PC-based檢測系統架構

- 軟體
  - 檢測與監測操作平台(Visual Signal)
  - 資料擷取軟體(DAQ API)
  - 振動與噪音分析模組(SVM)

- 硬體
  - 資料擷取卡(NI DAQ)
  - 加速規
  - 麥克風
  - 轉速計
  - 熱電偶
  - ...



# Visual Signal : 軟硬體整合平台



資料擷取硬體  
檔案  
使用者自建函數

輸入

雜訊濾除  
趨勢移除  
時間域分析  
頻率域分析  
時頻分析  
統計分析  
矩陣與數學運算  
MATLAB, DLL

分析

輸出

圖形  
檔案  
訊號產生器



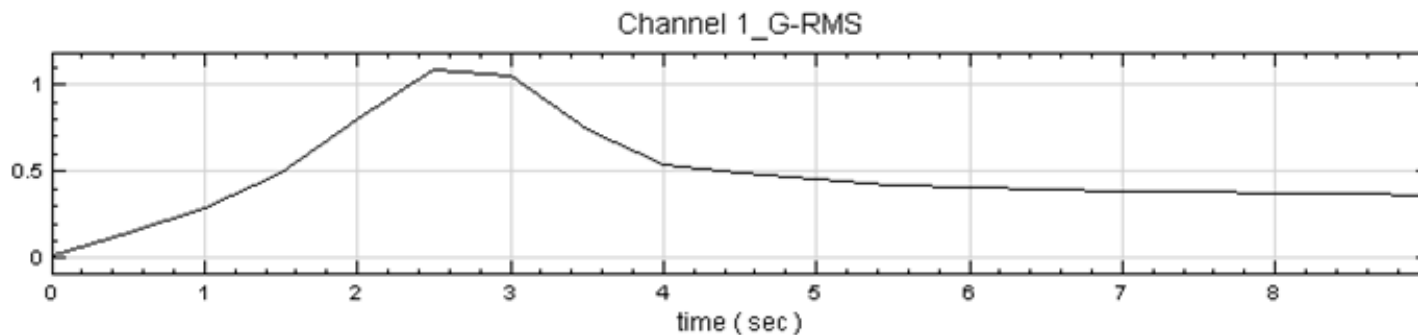
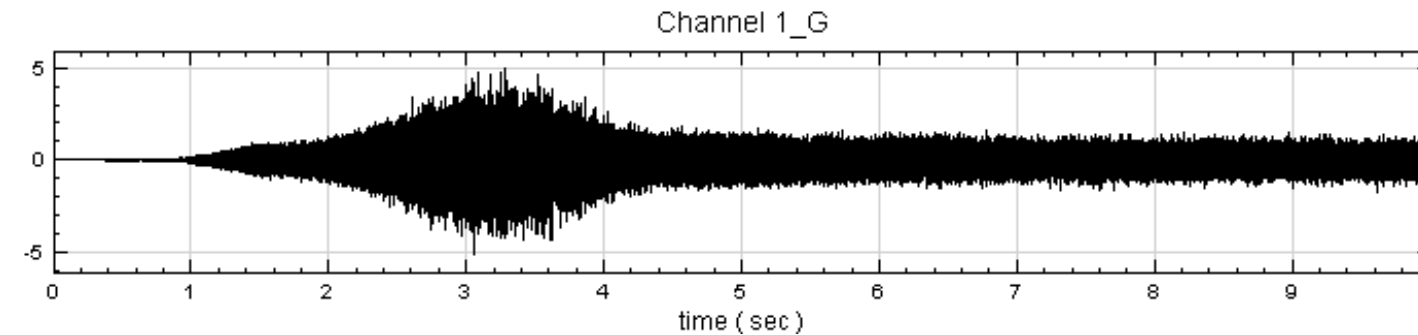
# Why Sound and Vibration Module?

- **Vibration Level**
  - RMS: RMS, Peak, Peak-to-Peak
  - Crest Factor
  - Peak : Max, Min, True Peak, True Peak-to-Peak
- **Sound Level**
  - A, B, and C Weighting
  - Octave
- **Order Tracking**
  - Digital Tacho
  - Order Tracking by STFT
  - Order Tracking by EnMorlet
- **Bearing Analysis**
  - Bearing Defect
  - Envelope Detection
- **Cepstrum**
- **Scale...**

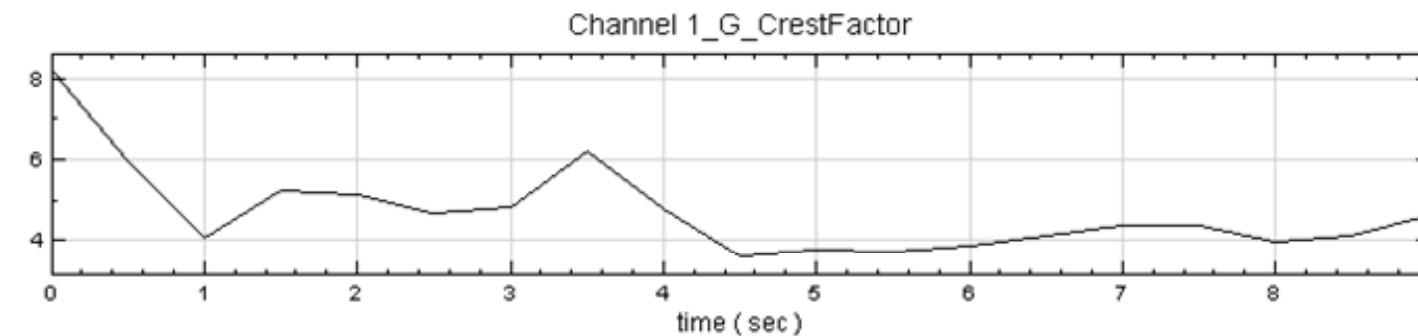




# Vibration Level: RMS & Crest Factor

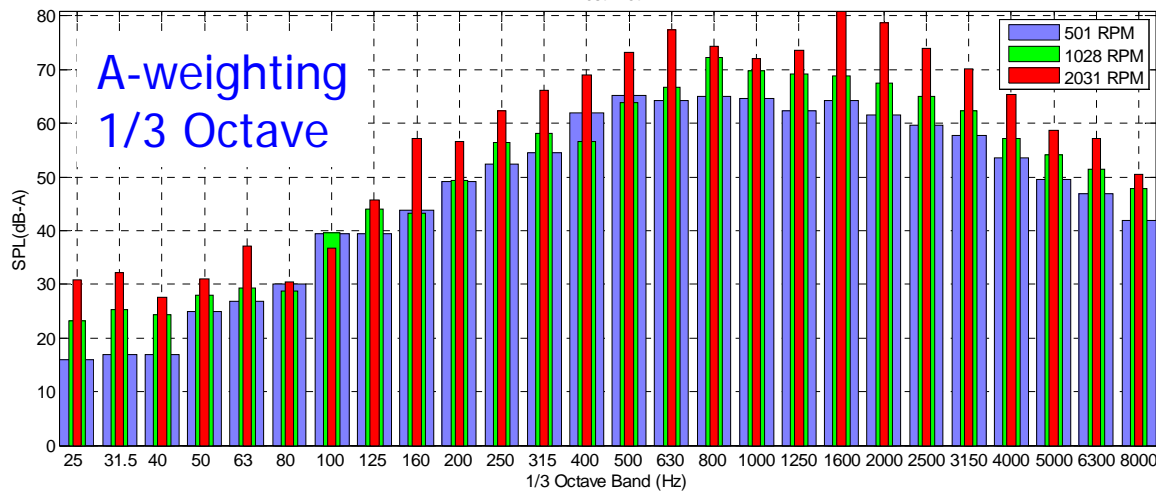
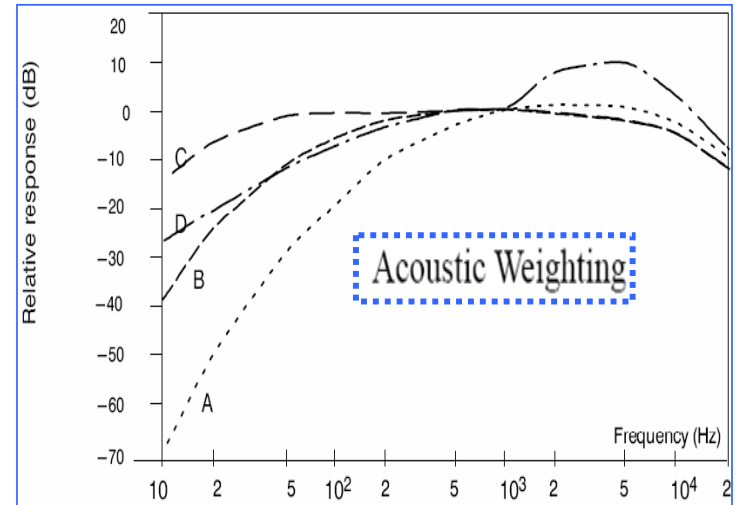
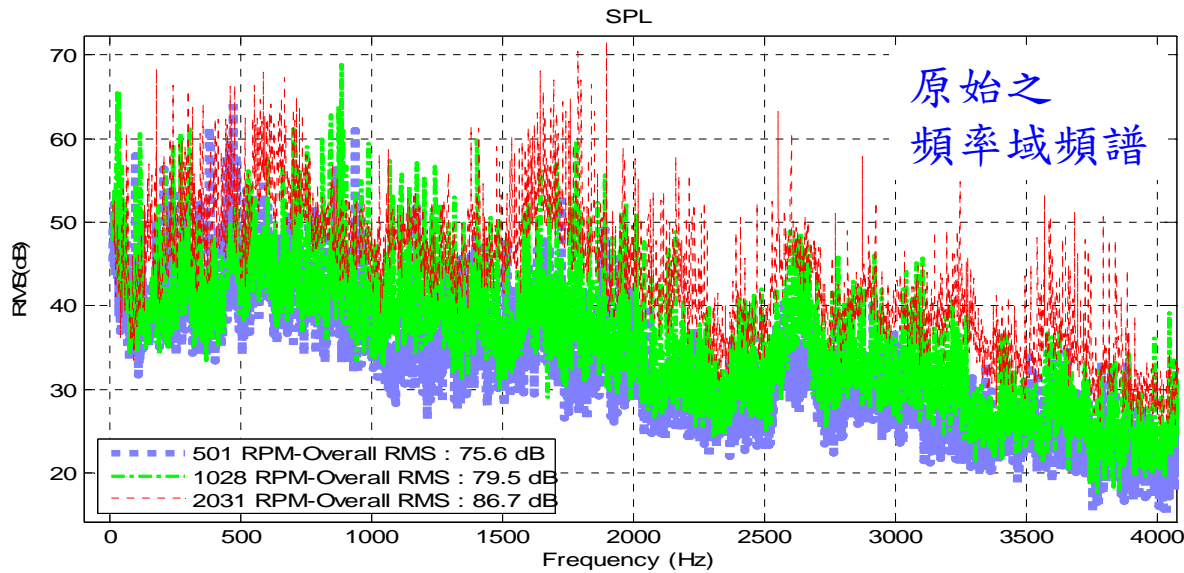


$$RMS = \sqrt{\frac{1}{T} \int_0^T a^2(t) dt}$$



$$CrestFactor = \frac{TruePeak}{RMS}$$

# Sound Level: Weighting & Octave



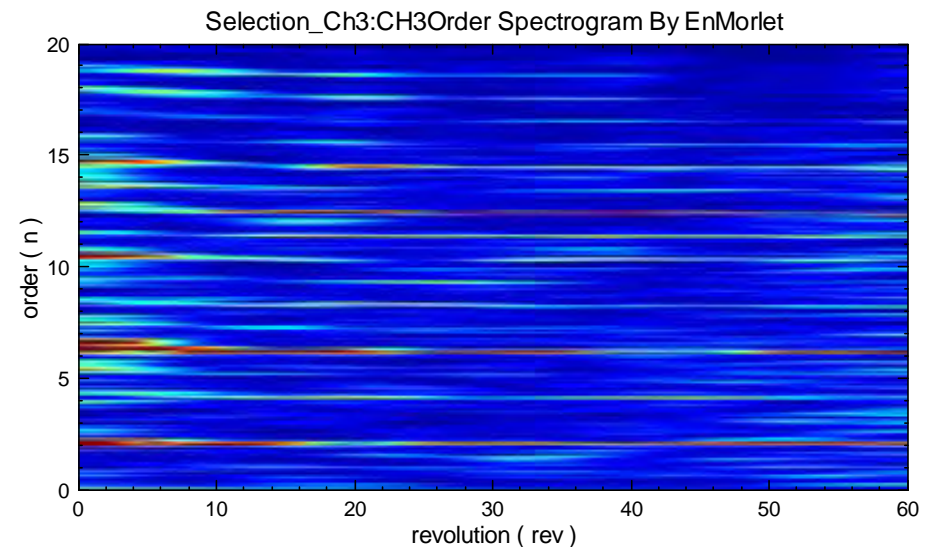
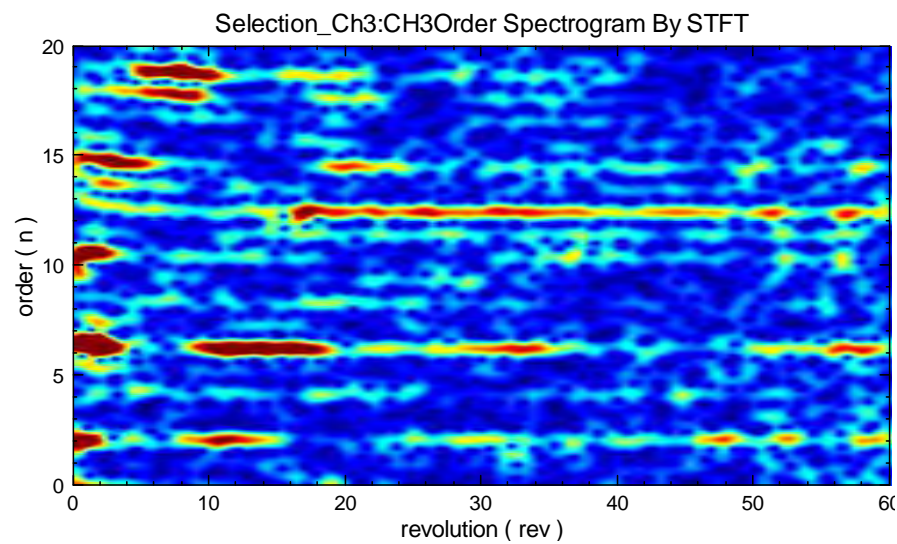
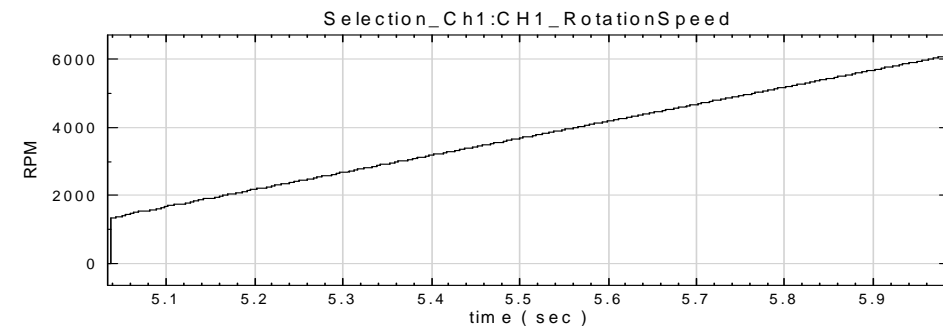
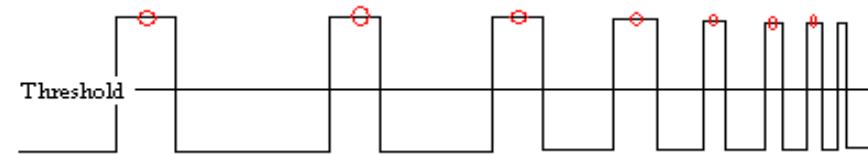
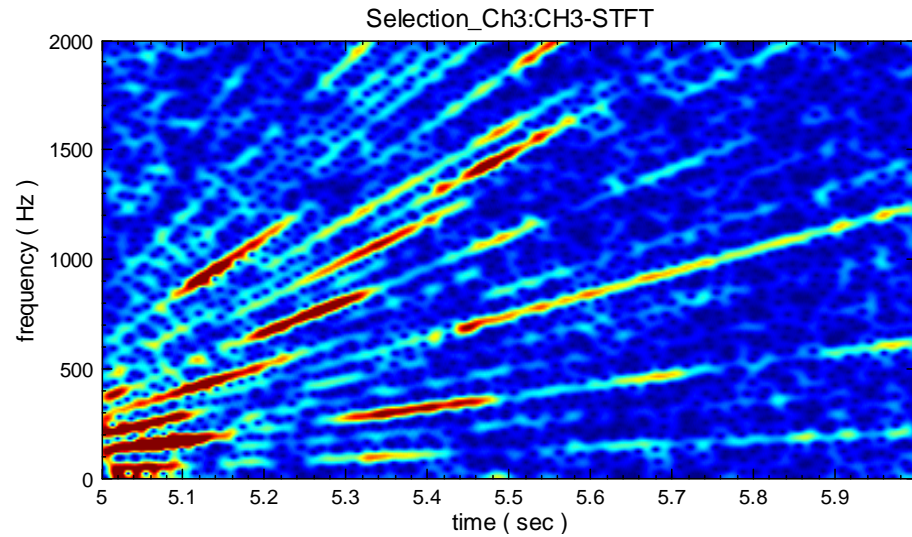
ThirdOctave :  $\frac{1}{3}$  八度音

Octave : 八度音

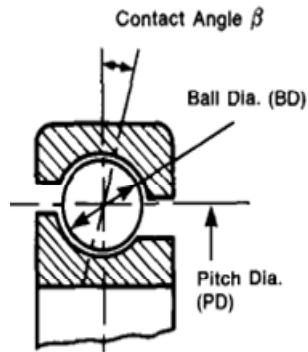
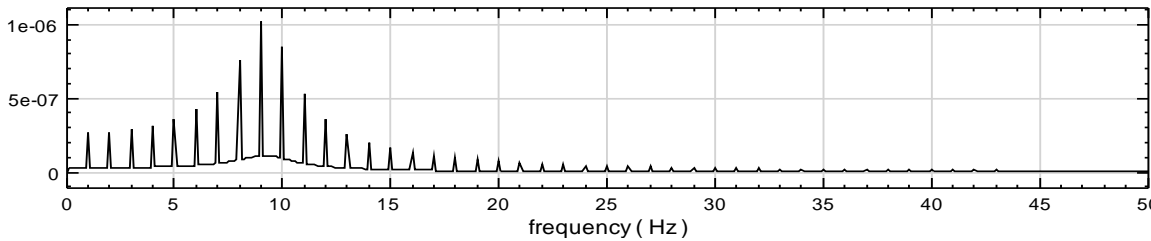
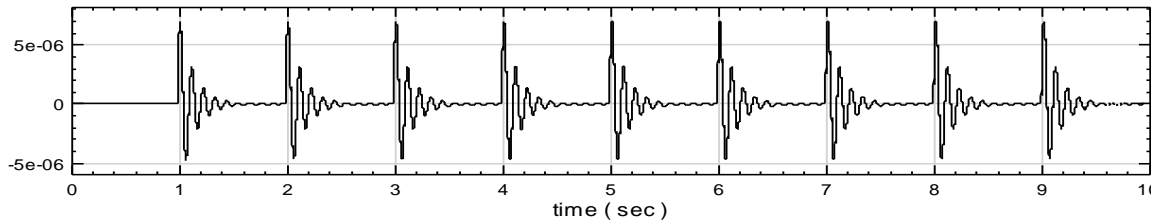
N\_Octave :  $\frac{1}{n}$  八度音 ( $n = \frac{1}{1}, \frac{1}{3}, \frac{1}{6}, \frac{1}{12}, \frac{1}{24}$ )

人耳效應

# Order Tracking



# Bearing Analysis



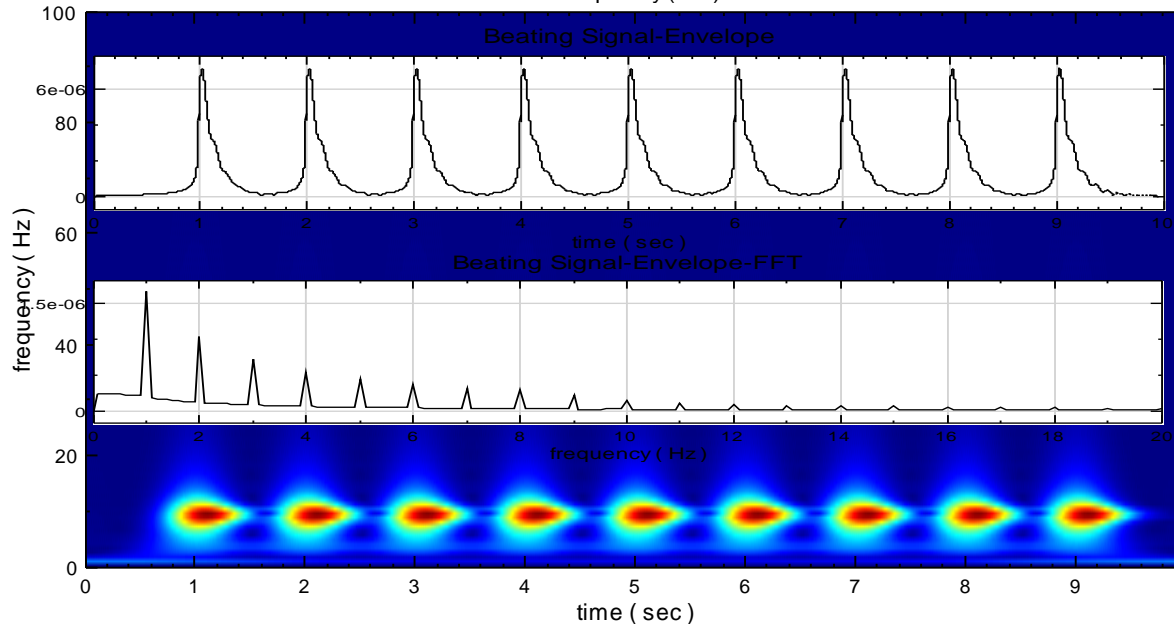
$n$  = number of balls or rollers  
 $f_r$  = relative rev./s between inner and outer races

Impact Rates  $f$  (Hz) (assuming pure rolling motion)

$$\text{For Outer Race Defect: } f(\text{Hz}) = \frac{n}{2} f_r \left( 1 - \frac{BD}{PD} \cos \beta \right)$$

$$\text{For Inner Race Defect: } f(\text{Hz}) = \frac{n}{2} f_r \left( 1 + \frac{BD}{PD} \cos \beta \right)$$

$$\text{For a Ball Defect: } f(\text{Hz}) = \frac{PD}{BD} f_r \left[ 1 - \left( \frac{BD}{PD} \cos \beta \right)^2 \right]$$

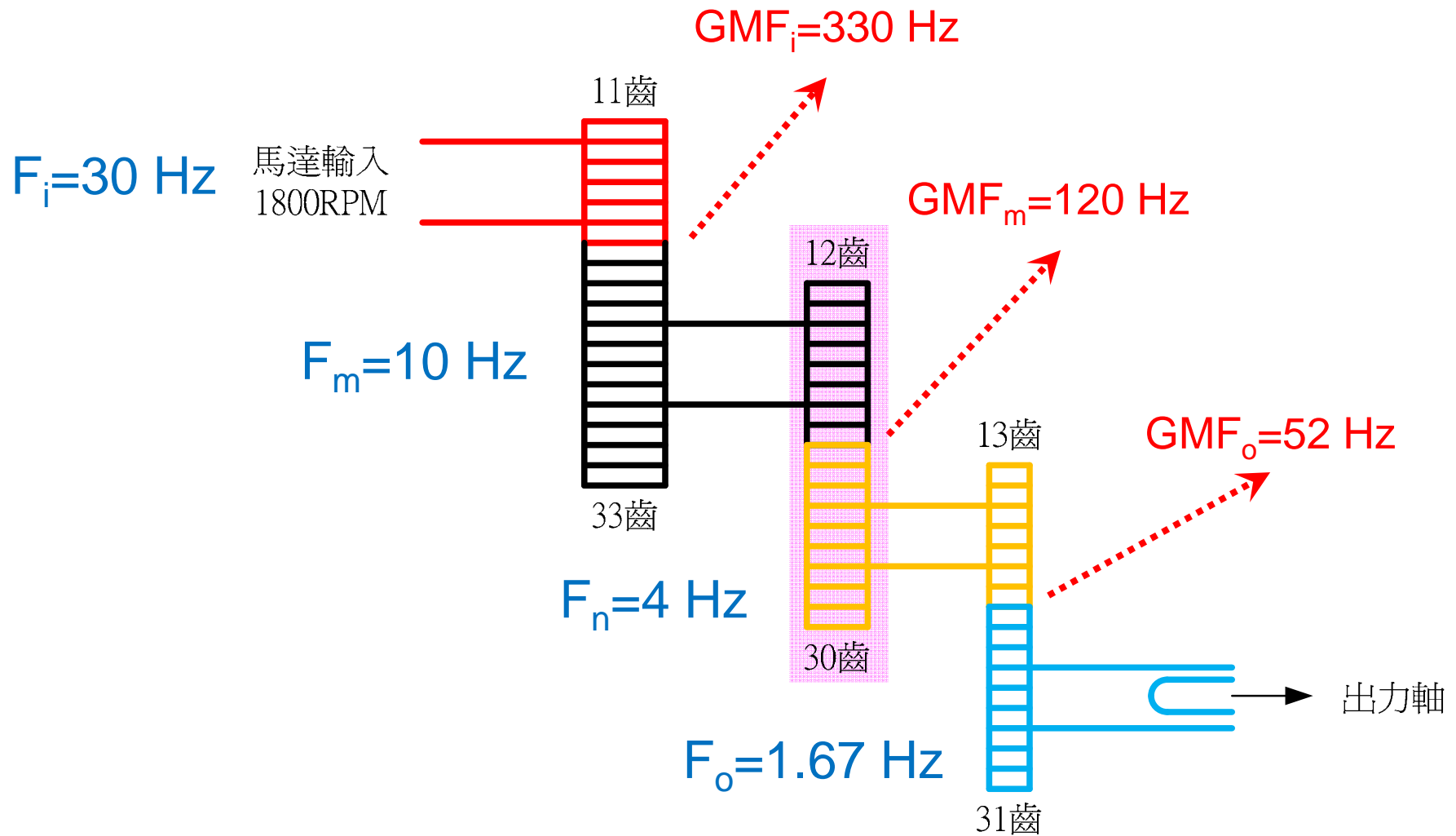




# 齒輪箱包絡頻譜分析



# 轉軸頻率與嚙合頻率

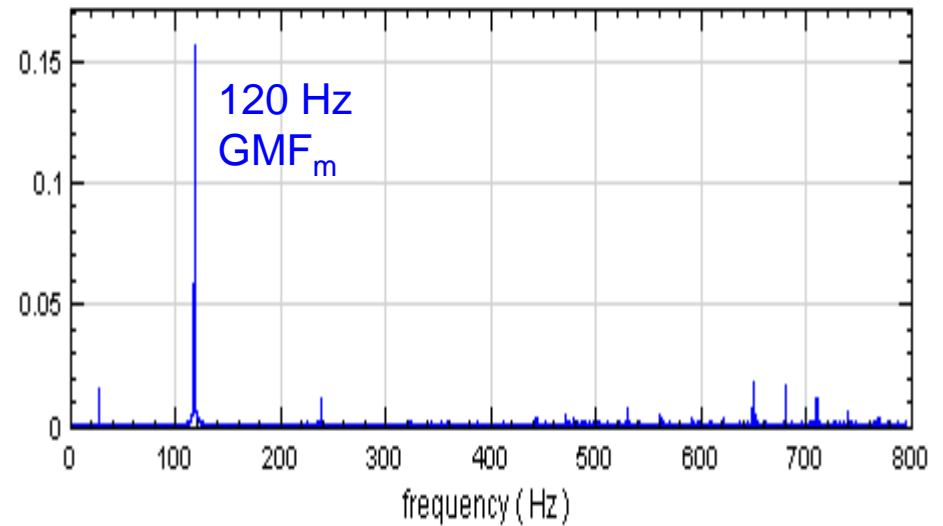
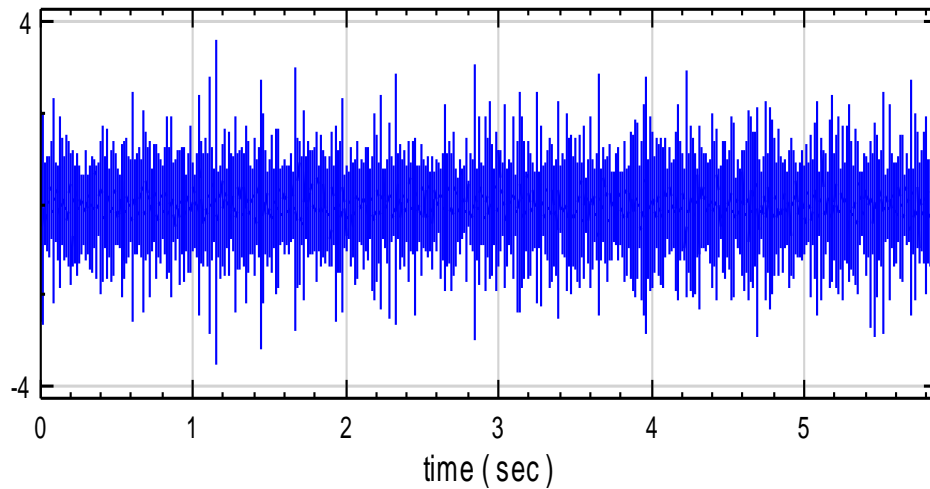




# 正常VS.異常齒輪箱振動訊號&頻譜

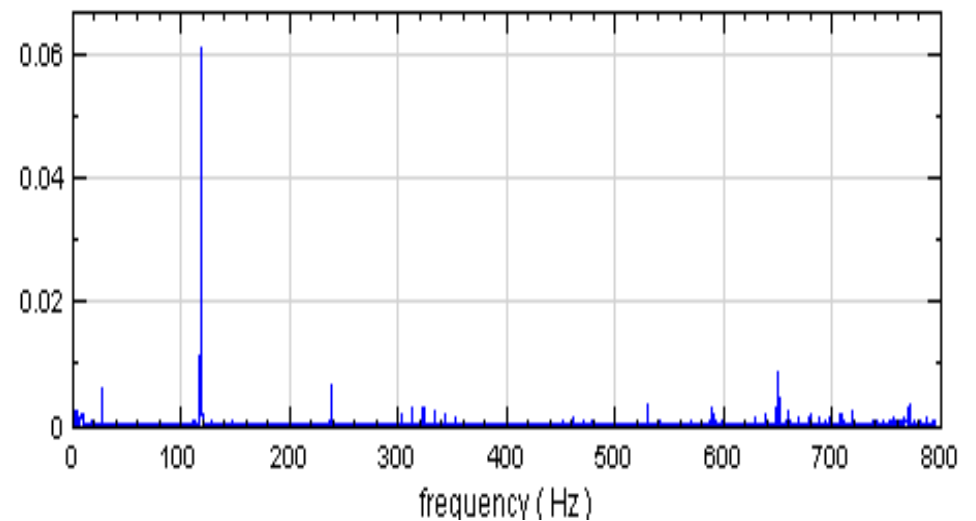
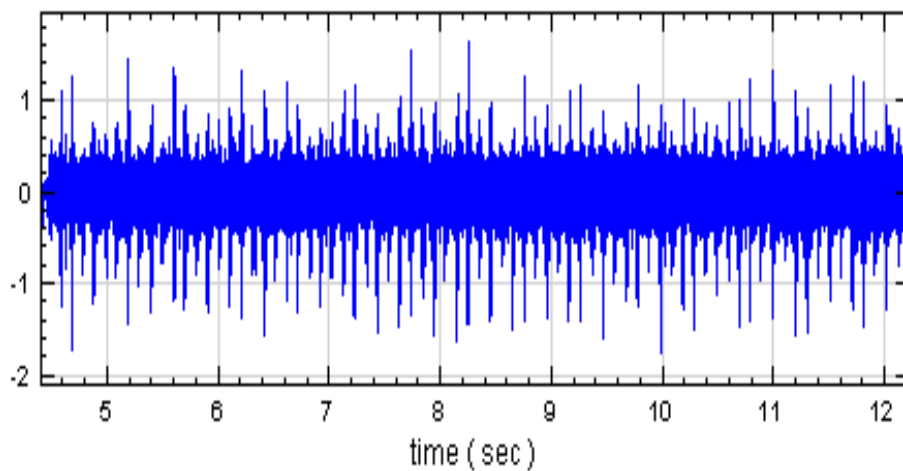
正常

DAQNI-1780-V-O-1\_Ch2:CH2-FFT



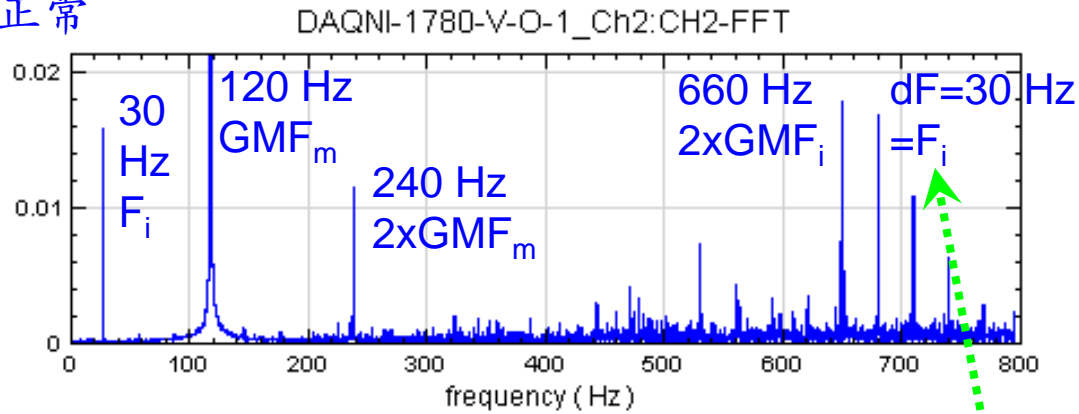
異常

NoGood正轉-FFT

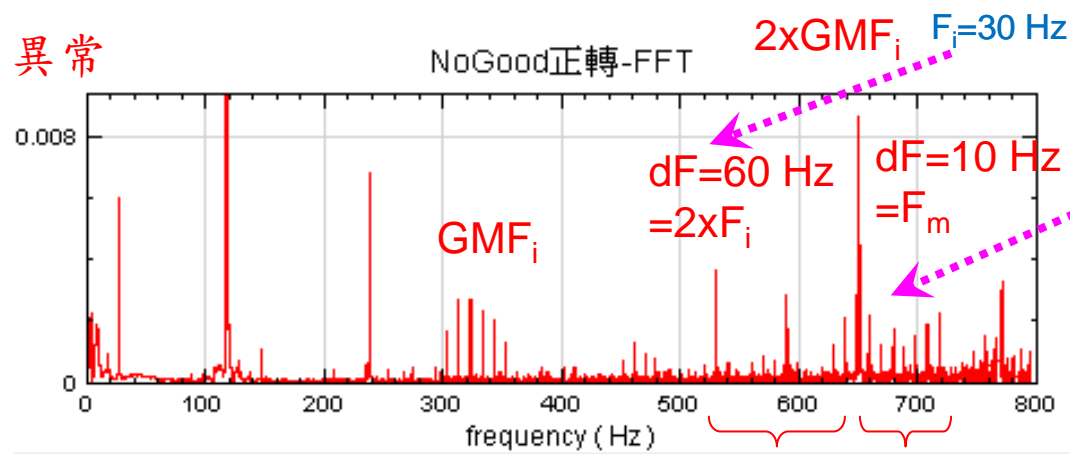


# 正常vs.異常齒輪箱振動訊號：頻譜比較(Zoom-in)

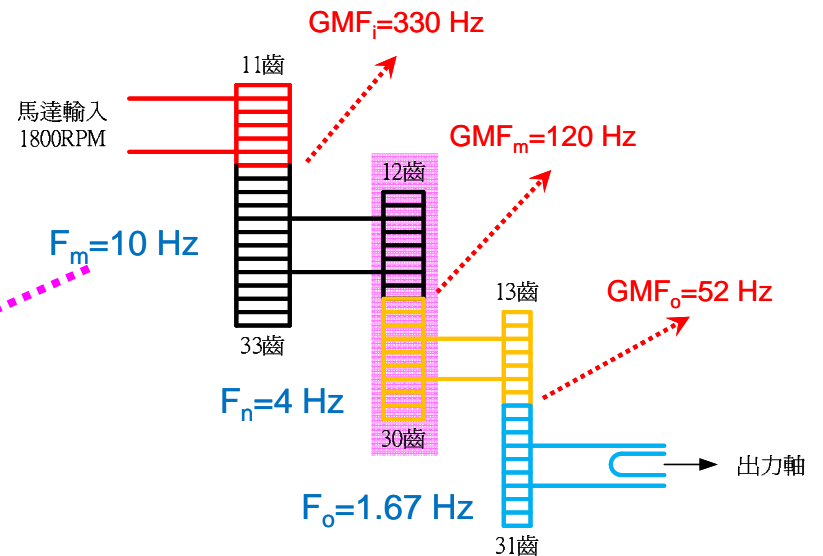
正常



異常



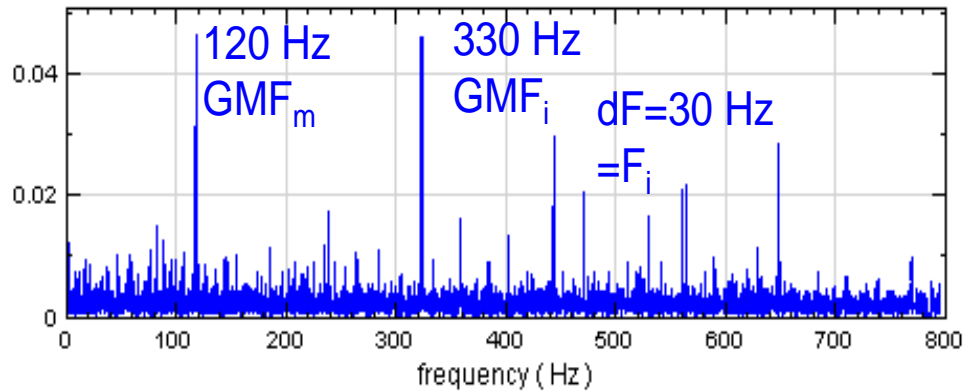
$dF=10$  Hz  $=F_m$       i軸鬆脫 不對心      m軸 偏心





# 正常VS.異常齒輪箱振動訊號：包絡線頻譜

正常齒輪箱之包絡線頻譜



異常之  
轉速調變頻率

異常之  
嚙合頻率

異常之齒輪  
12齒

$GMF_i=330\text{ Hz}$

$GMF_m=120\text{ Hz}$

$GMF_o=52\text{ Hz}$

10 Hz

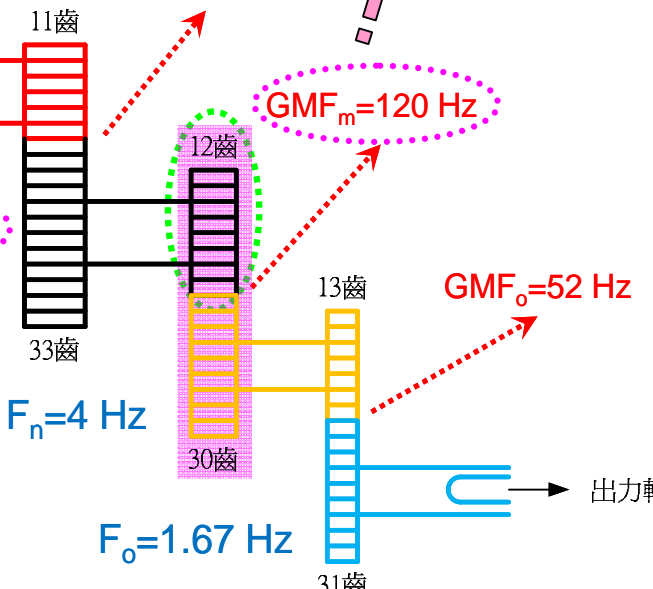
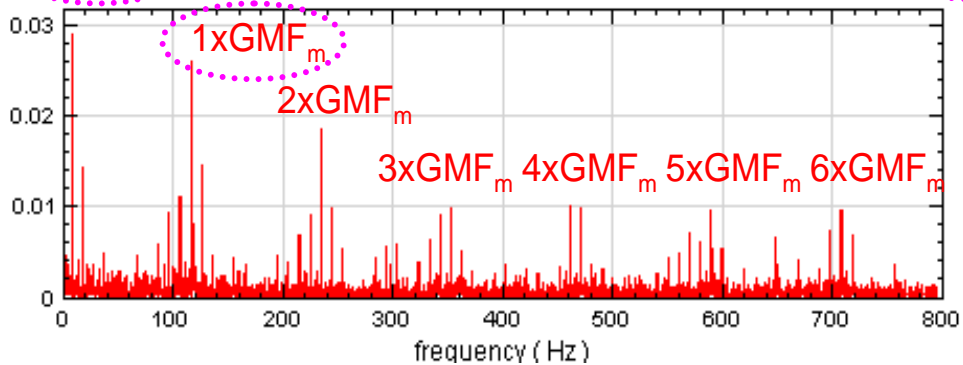
$F_n=4\text{ Hz}$

$F_o=1.67\text{ Hz}$

出力軸

$dF=10\text{ Hz} = F_m$

異常齒輪箱之包絡線頻譜



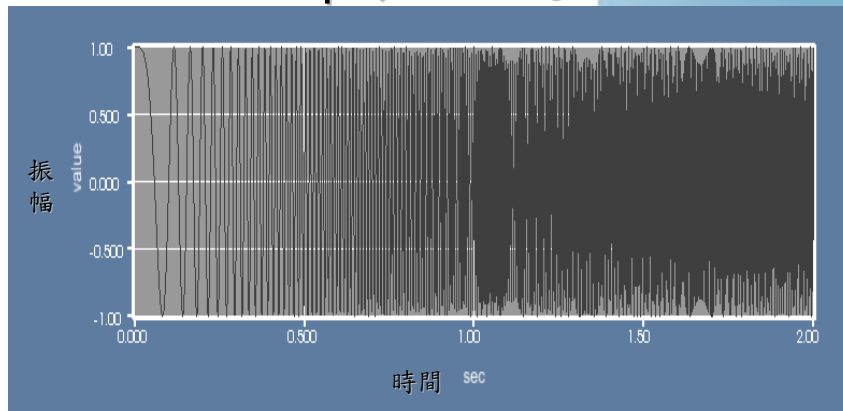


# Time-Frequency Analysis (TFA)

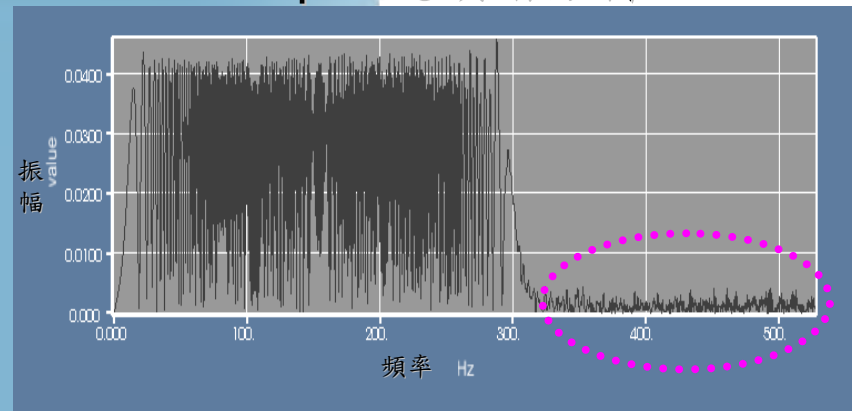


# Why 高解析時頻分析? ⇨ 細微異常檢出

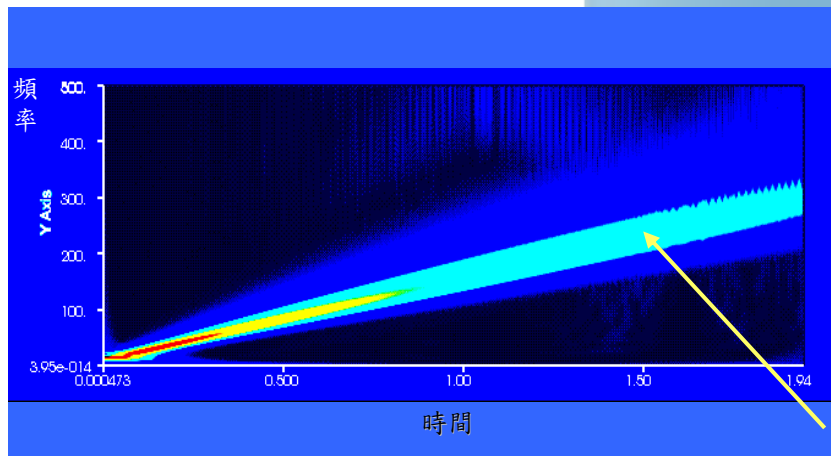
## Chirp原始訊號



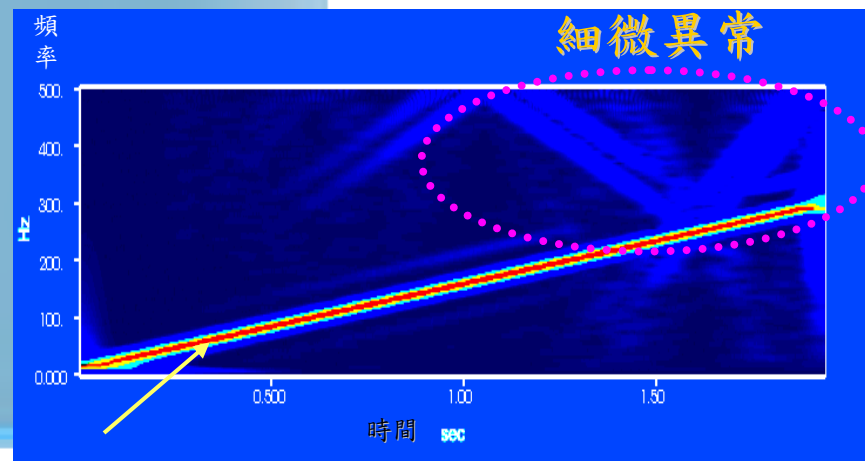
## Chirp訊號頻譜分析



## Morlet Transform時頻圖



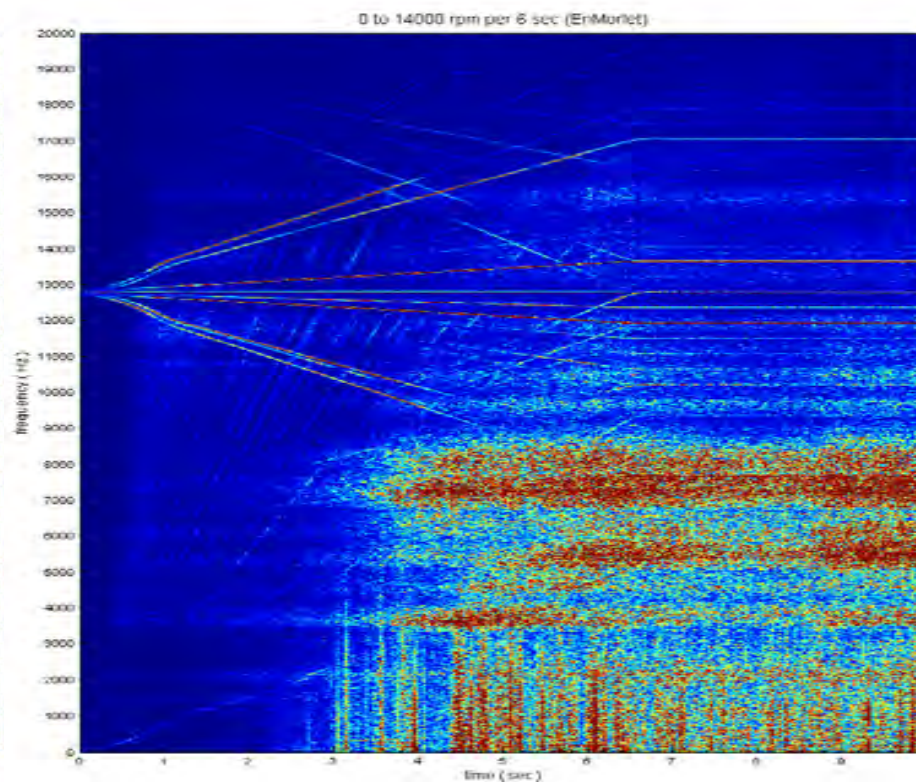
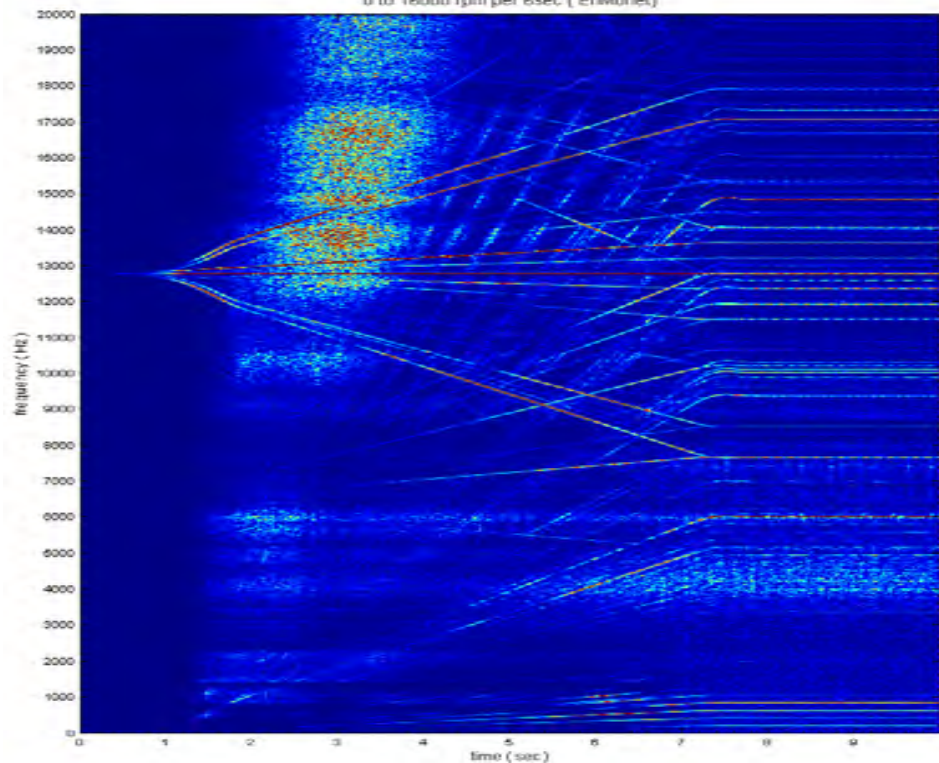
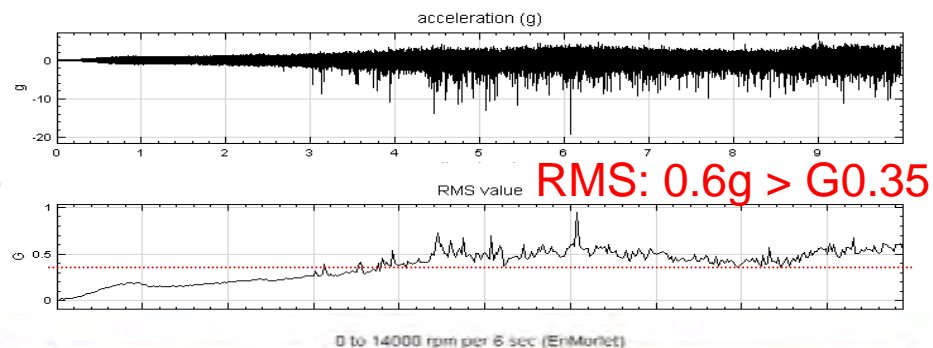
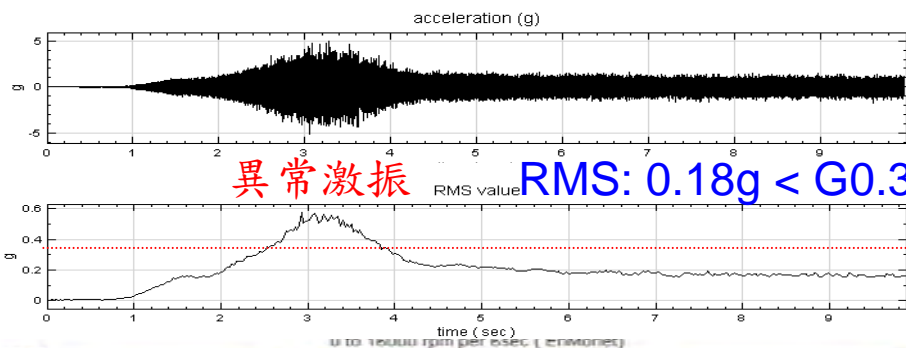
## Enhanced Morlet Transform



色彩表示其能量或振幅

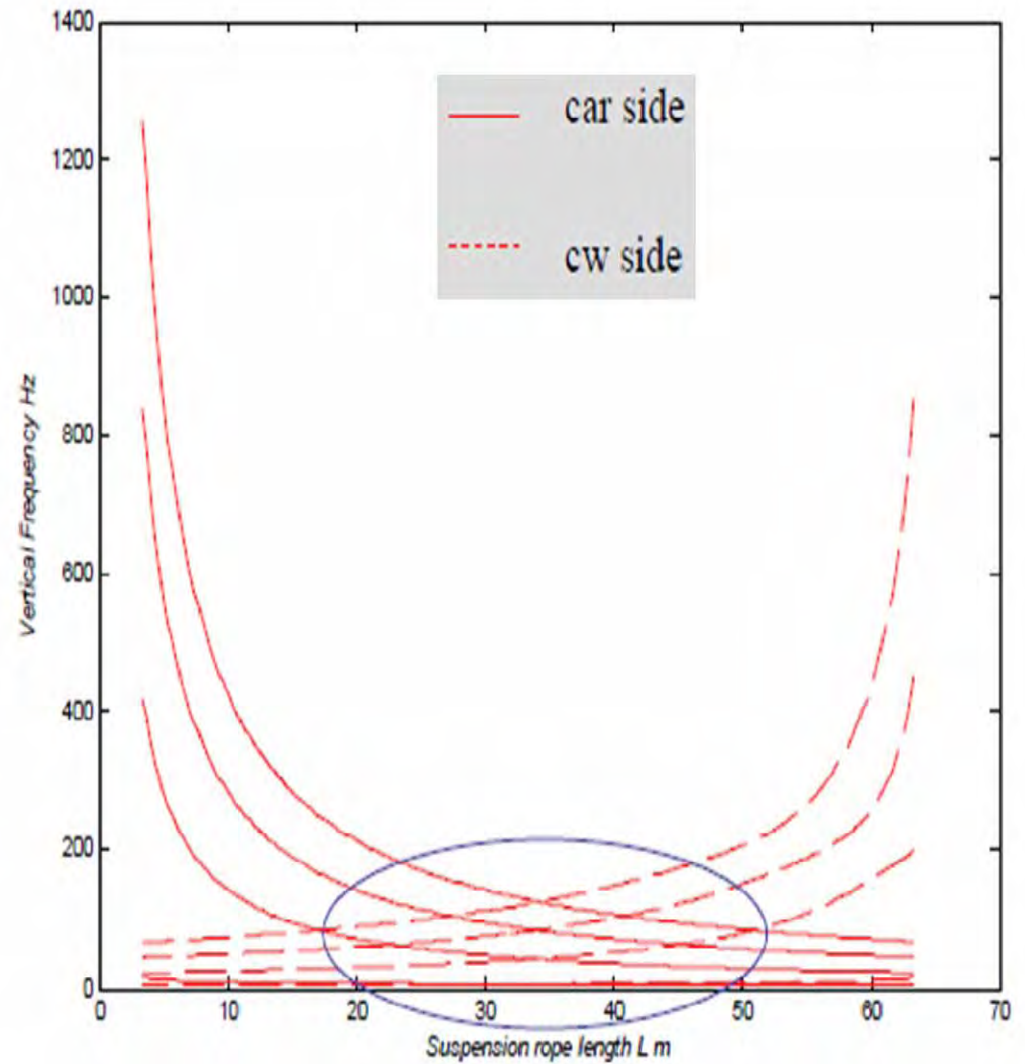
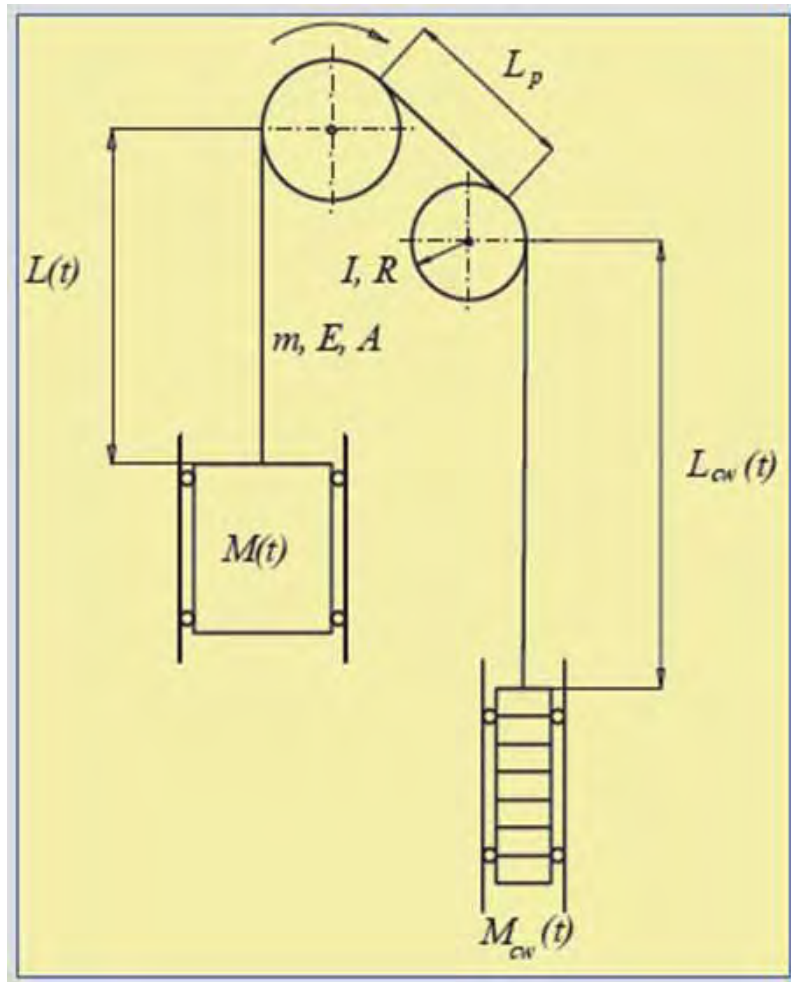
# Why 變轉速時頻分析?

⇒ 轉速倍頻、共振頻段、異常激振、頻率調變

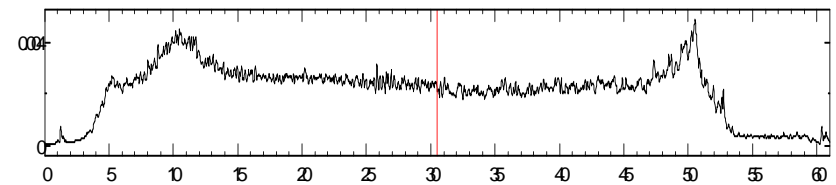
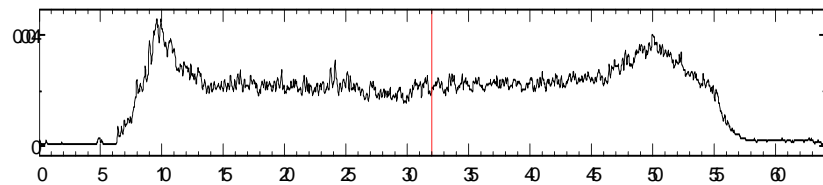
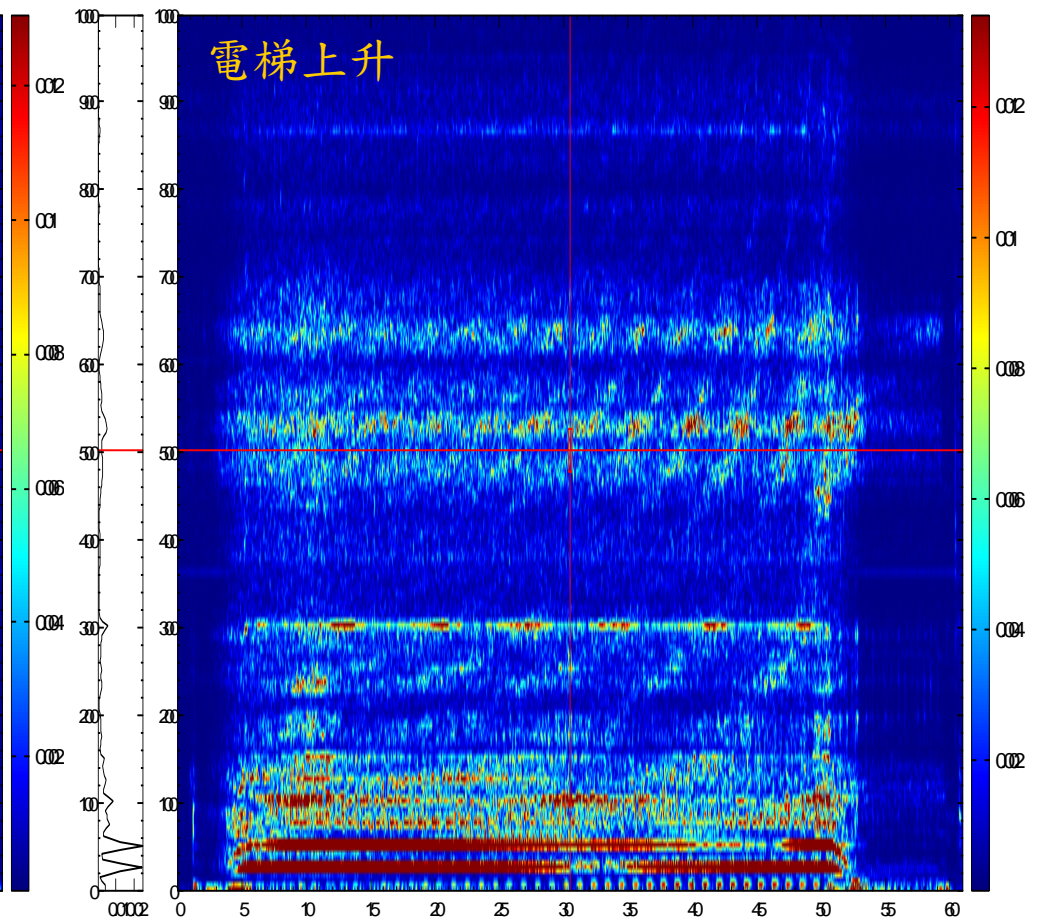
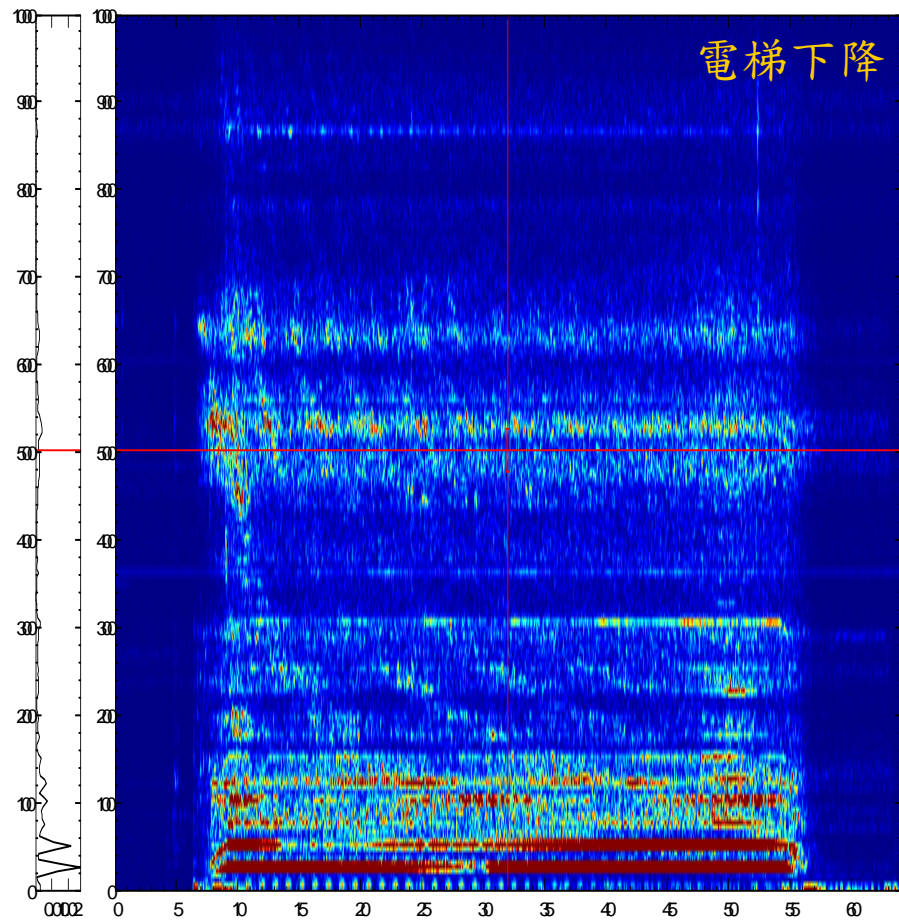




# 電梯系統自然頻率



# 電梯系統振動時頻分析



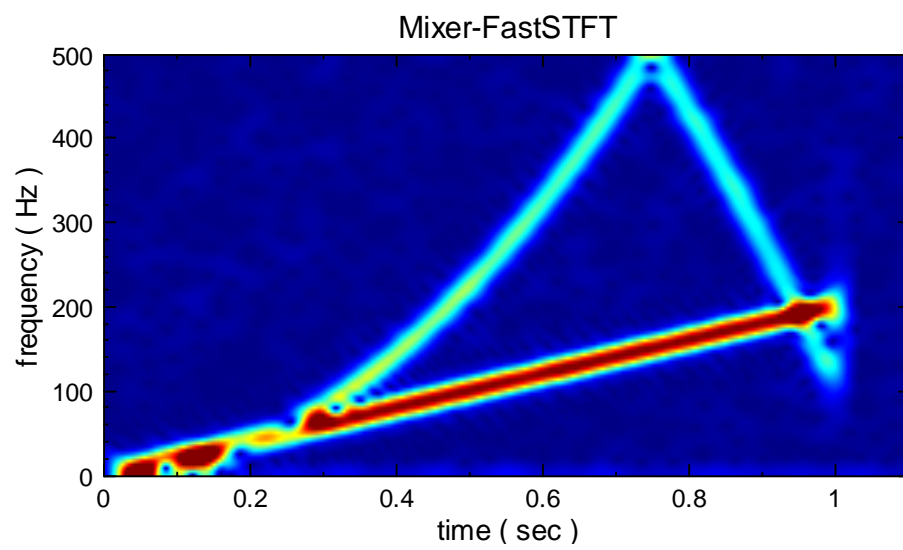
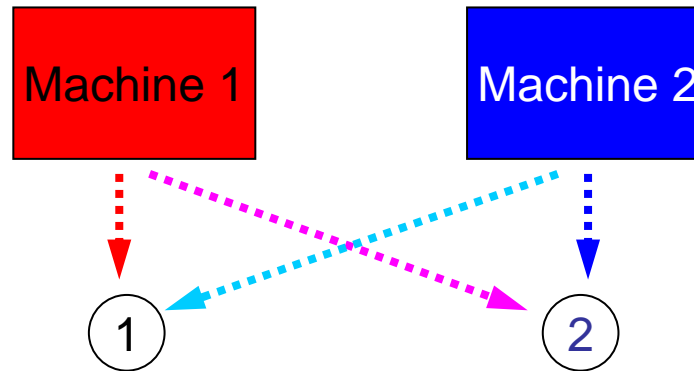


# Independent Component Analysis (ICA)

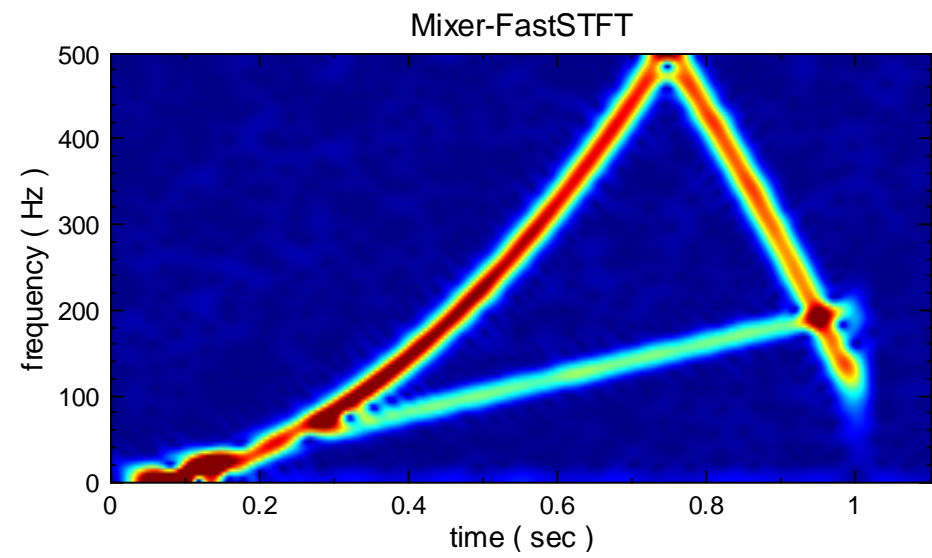




# 2個量測點之混合訊號



1



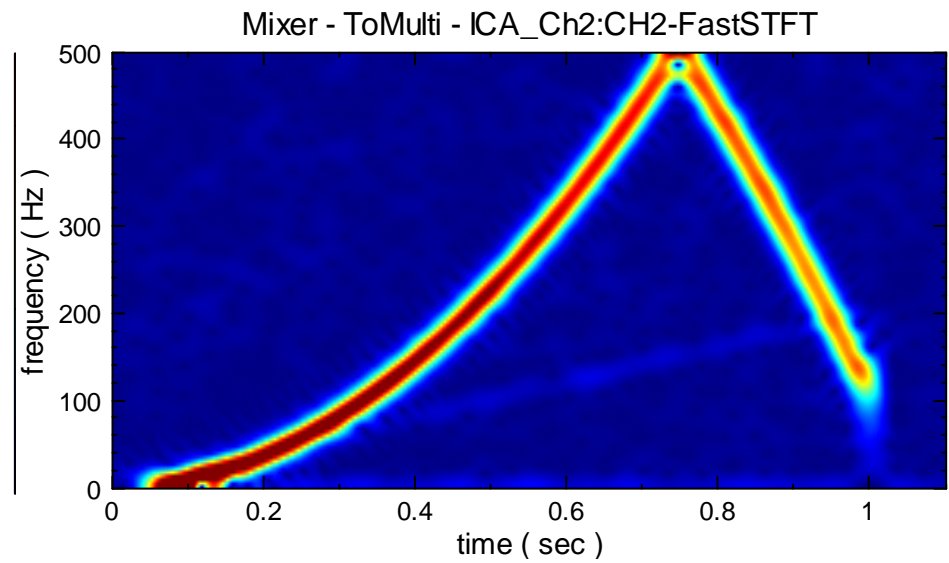
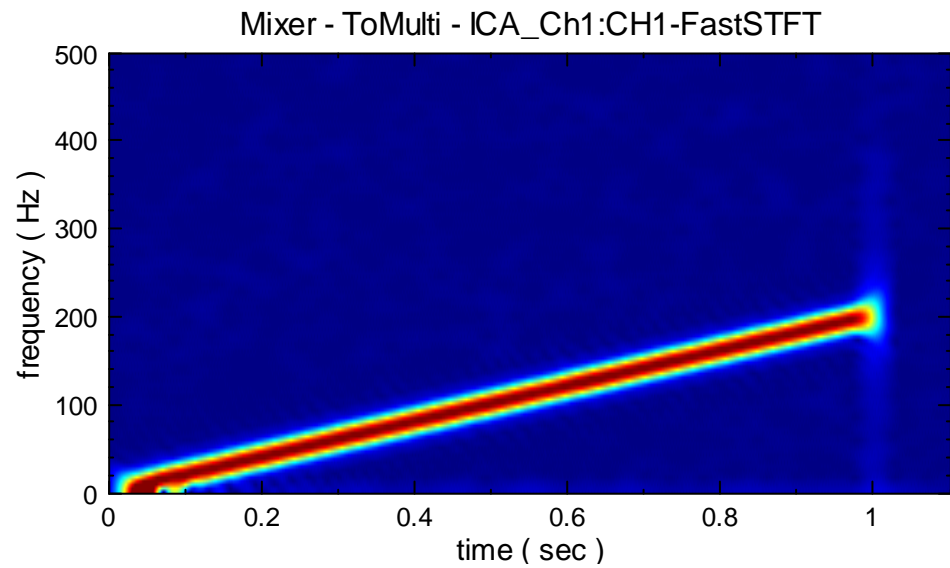
2



# ICA分離 ⇒ 2個獨立振動源

Machine 1

Machine 2

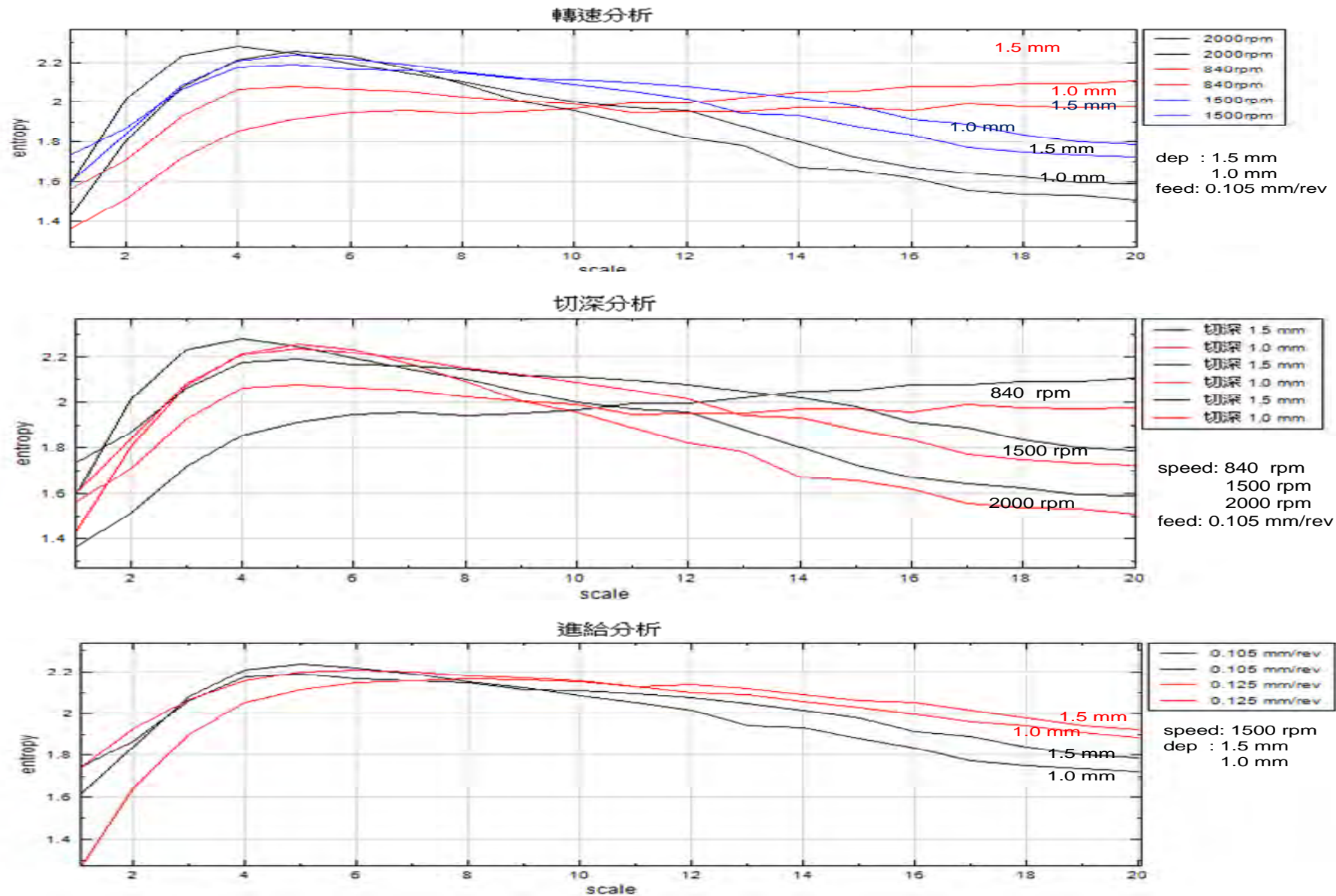




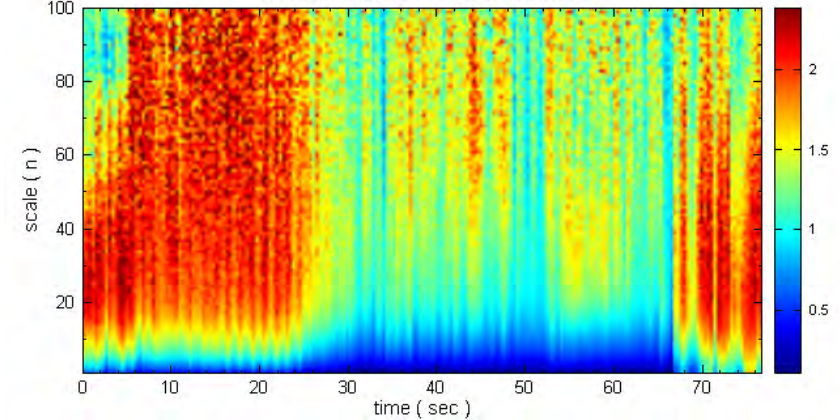
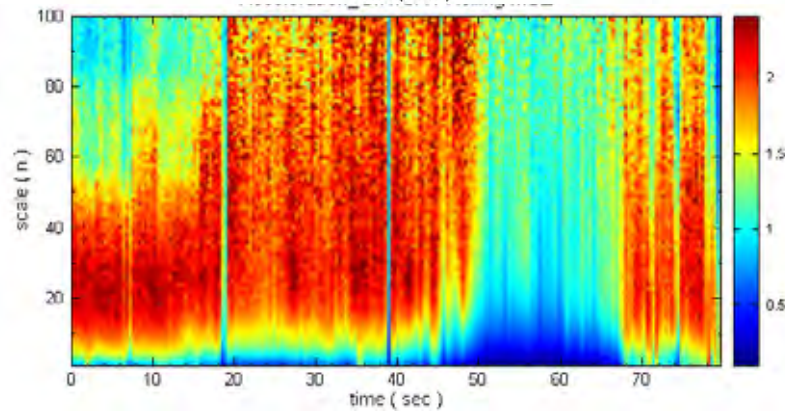
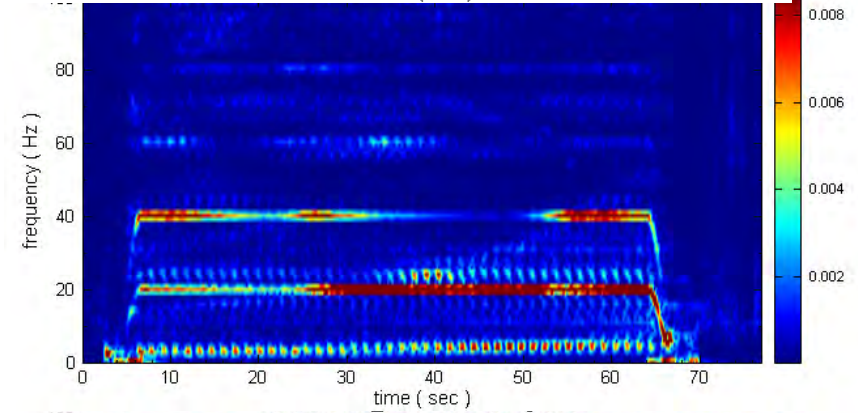
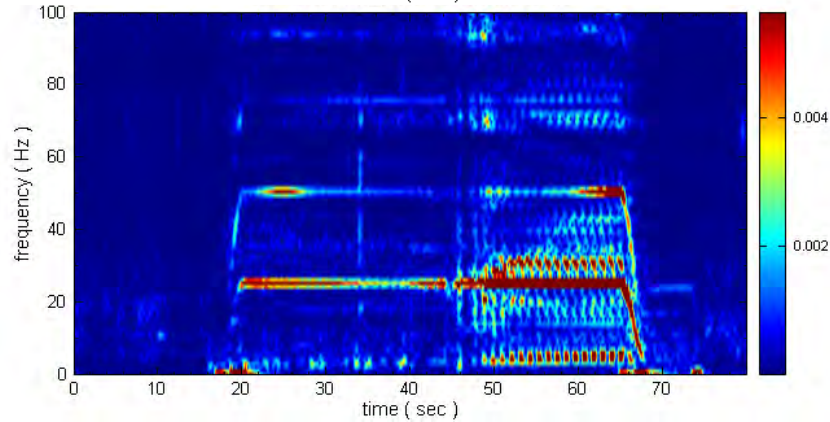
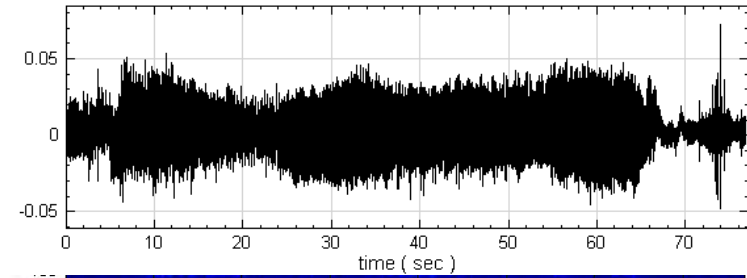
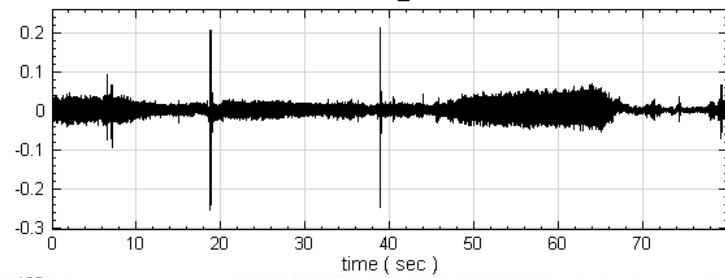
# Multi-Scale Entropy (MSE)



# MSE：參數明顯度判別 $\Rightarrow$ 轉速 > 切深 > 進給



# Rolling MSE : 電梯振動





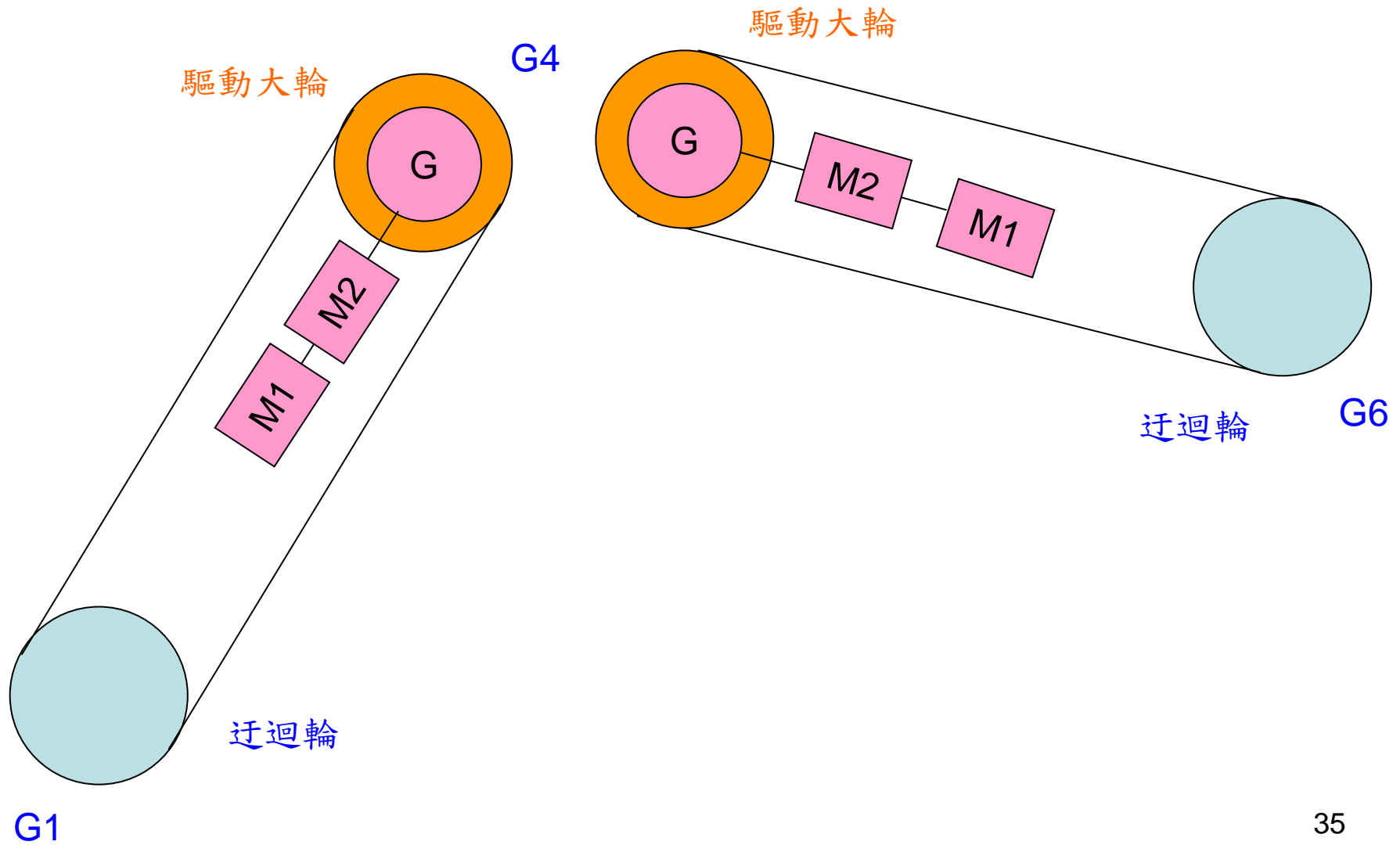


# 纜車之振噪檢測

# 貓纜路線圖



# 纜車動力系統

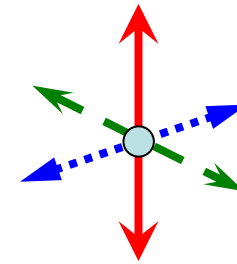


# 激振頻率 vs. 自然頻率 ⇨ 異常共振



- ✓ 轉動激振頻率
- ✓ 驅動驅動頻率
- ✓ 塔柱滾輪激振頻率
- ✓ 流體激勵頻率

...



驅動頻率： $\Omega_n = 2n(V_c/R_d)$ ,  
 $n = 1, 2,$





# 量測硬體設置



麥克風(車廂內)  
量測乘客感受之噪音



加速規(車廂框架)  
量測纜繩傳遞至車體之振動



加速規(車廂天花板)  
量測發聲源之異常共振

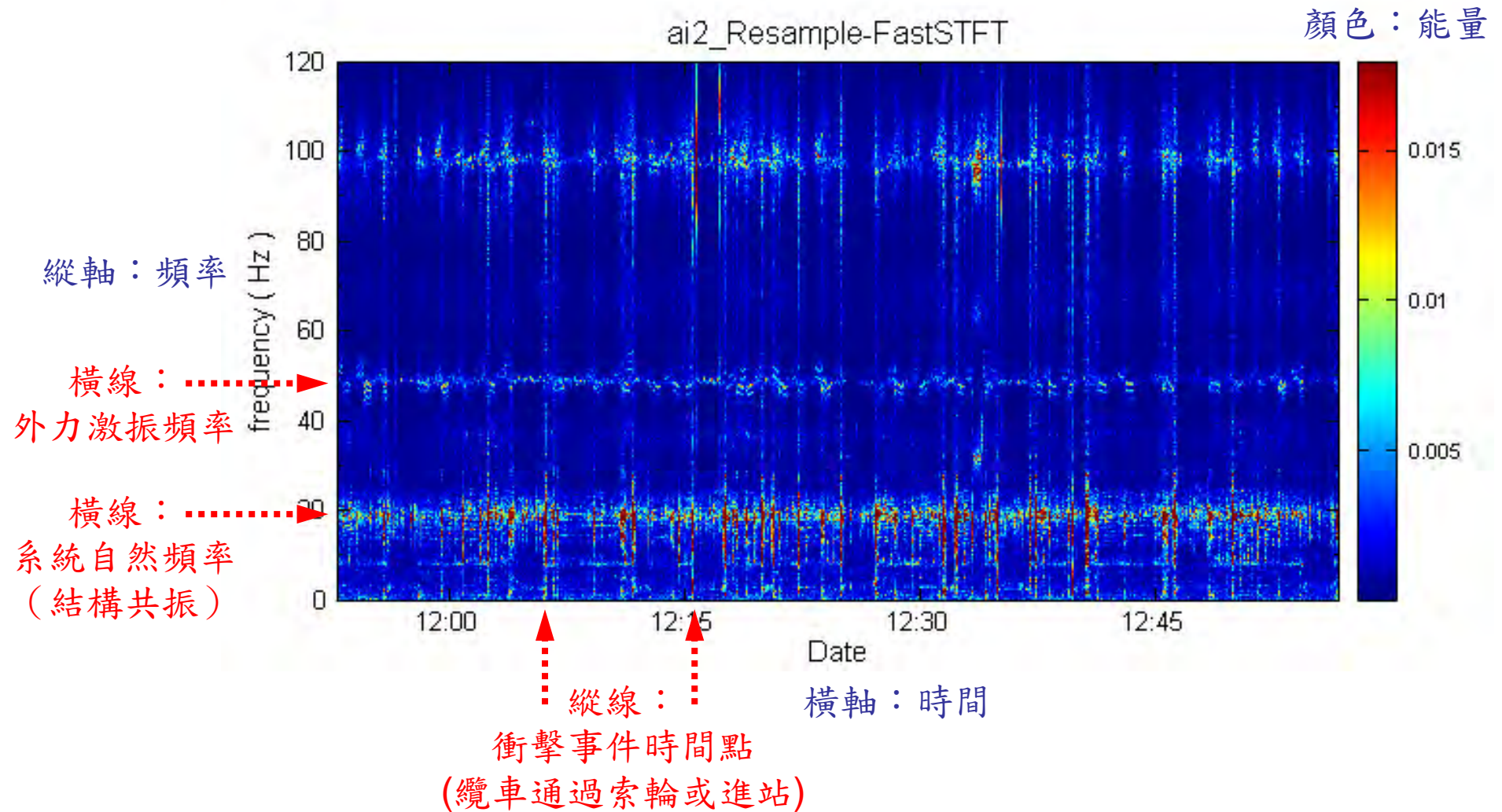
NI DAQ



TD1A

訊號擷取卡+筆記型電腦  
將物理訊號數位化並儲存

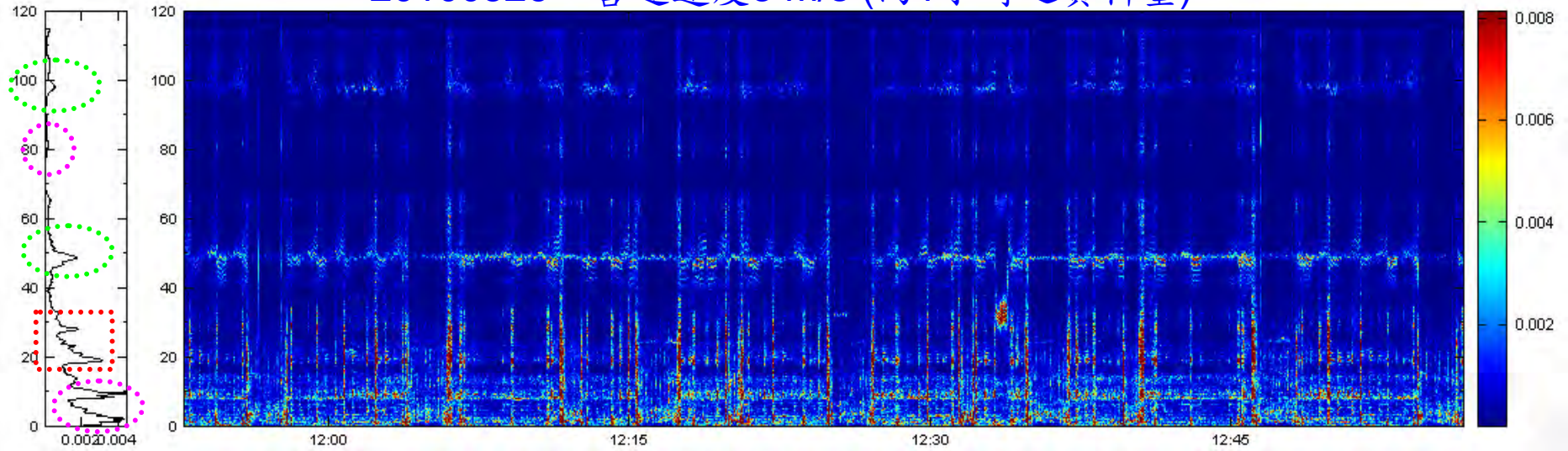
# 時頻圖之物理含意



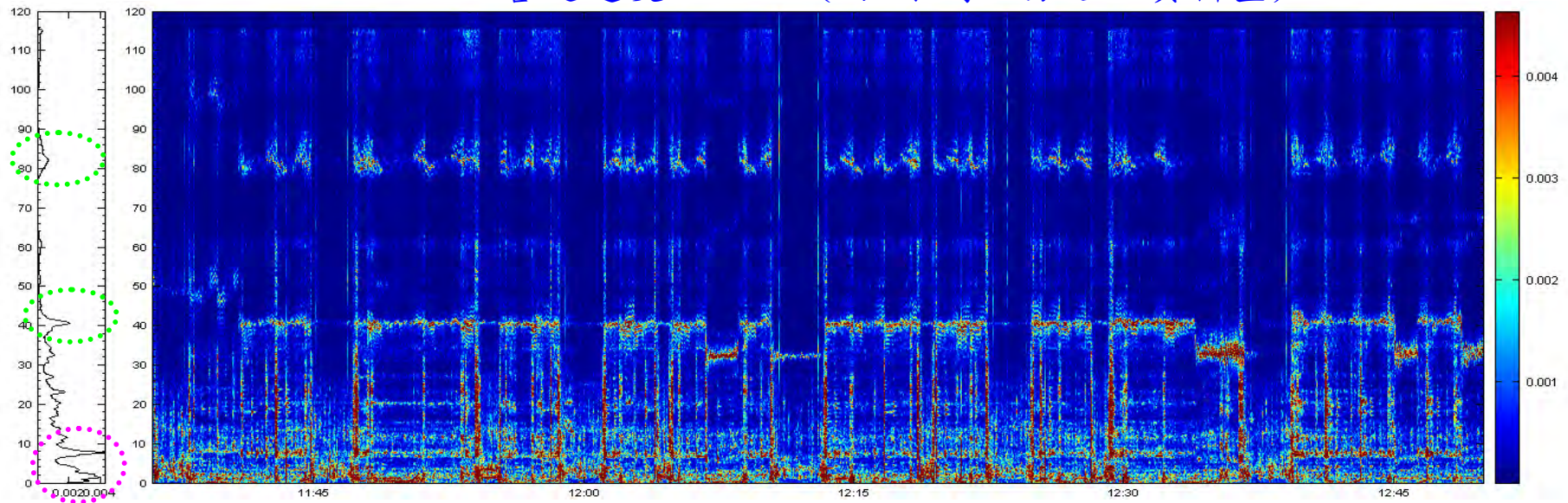


# 營運速度對系統穩定性之影響

20100526：營運速度3 m/s (約1小時之資料量)



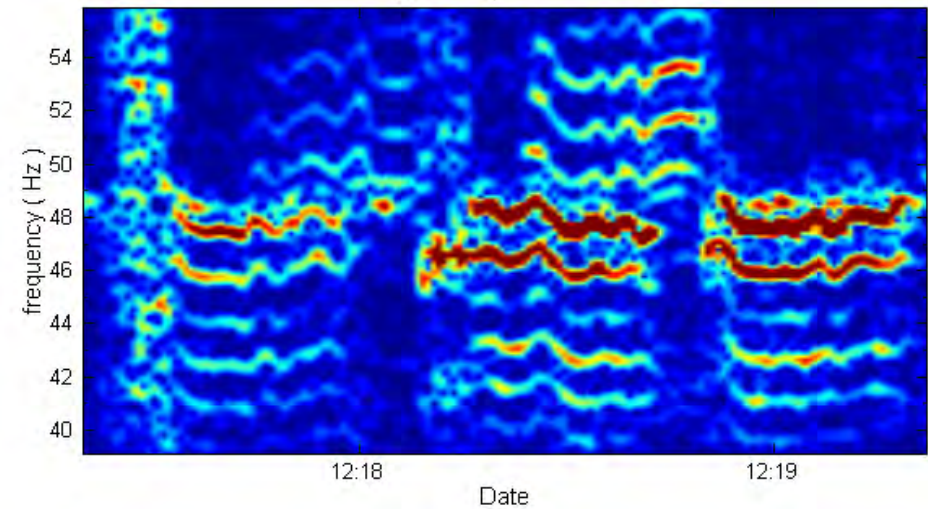
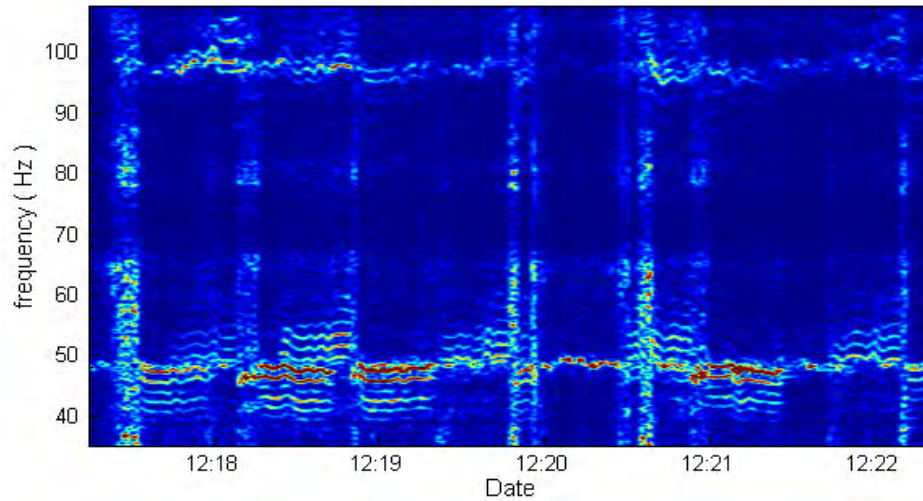
20100429：營運速度2.5 m/s (約1小時15分鐘之資料量)



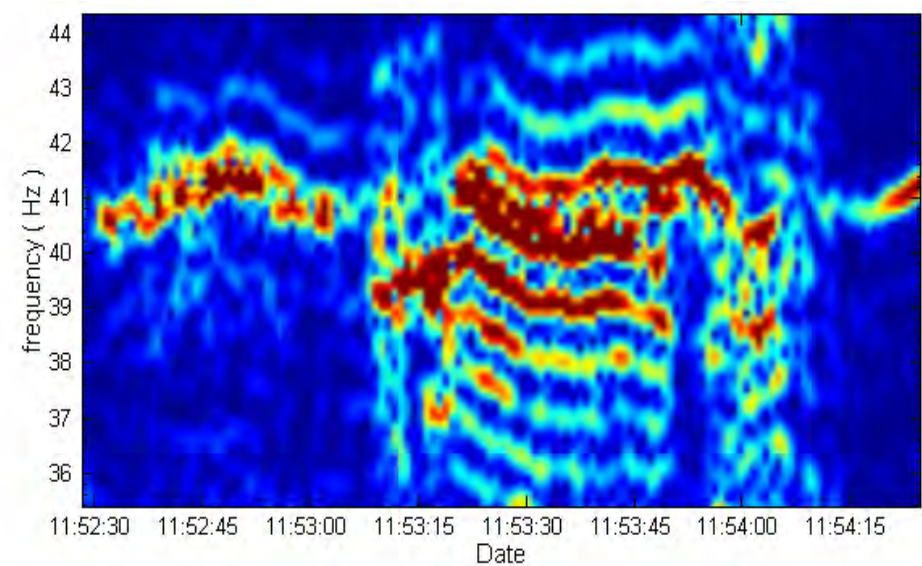
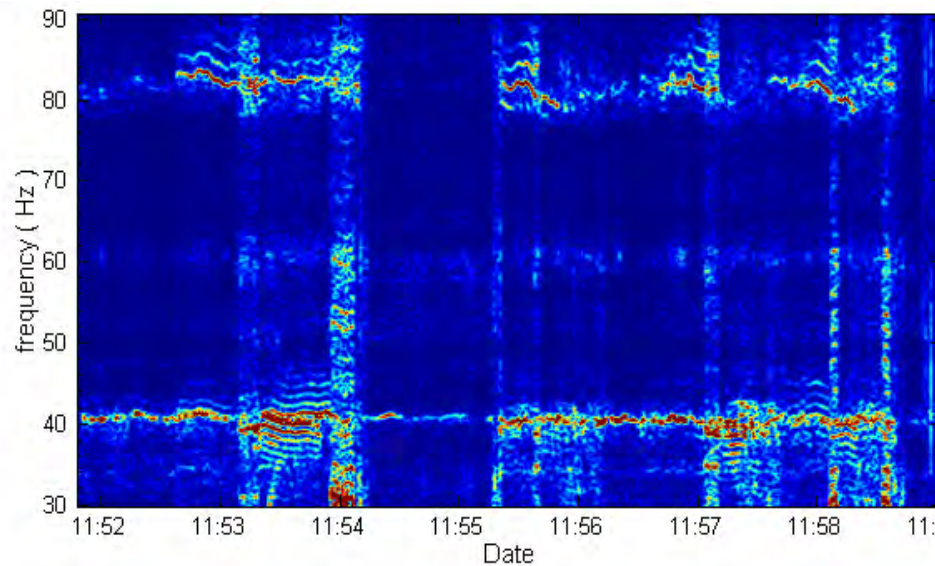


# 營運速度對系統穩定性之影響

20100526 : 營運速度3 m/s



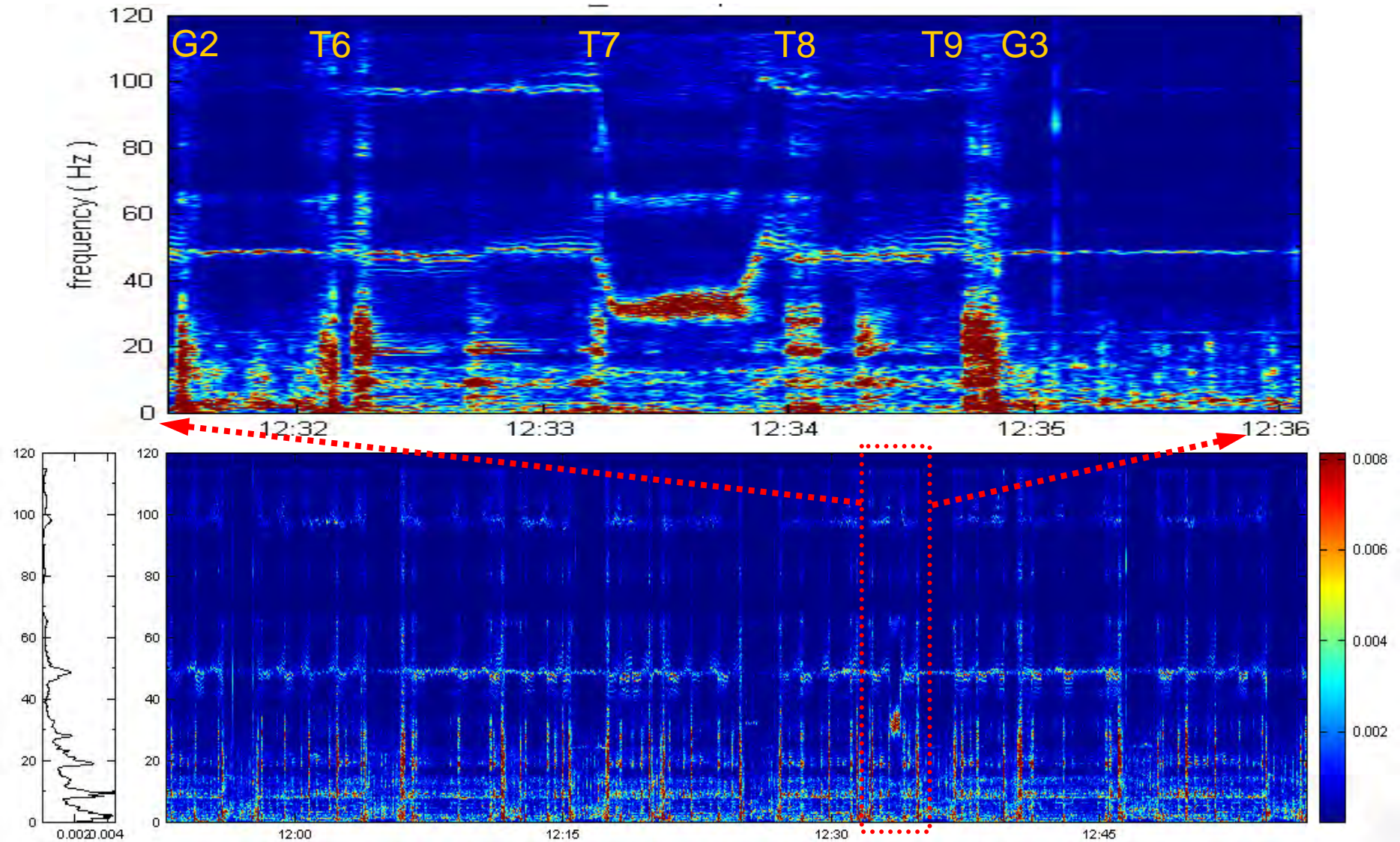
20100429 : 營運速度2.5 m/s





# 營運速度對系統穩定性之影響

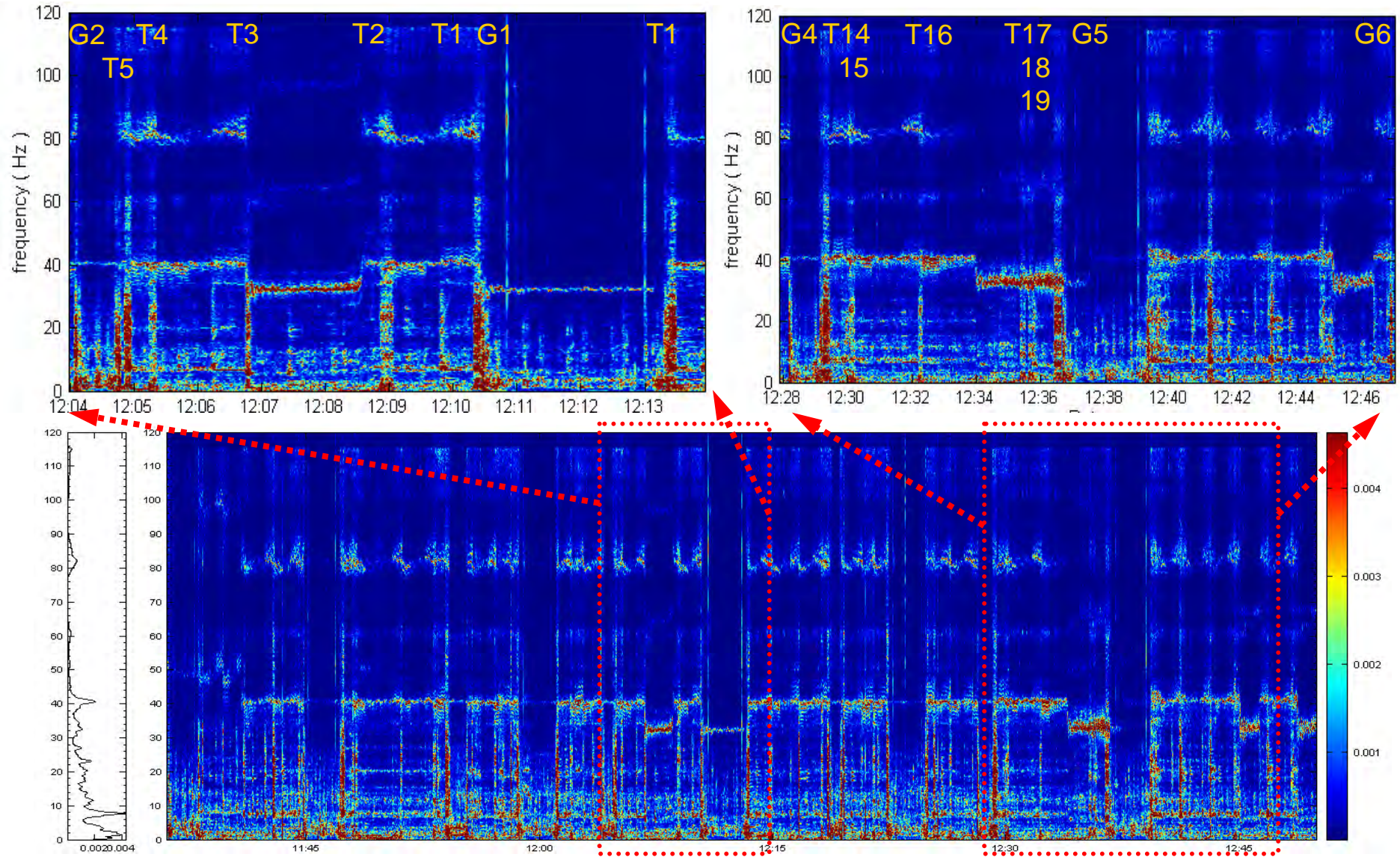
20100526：營運速度3 m/s





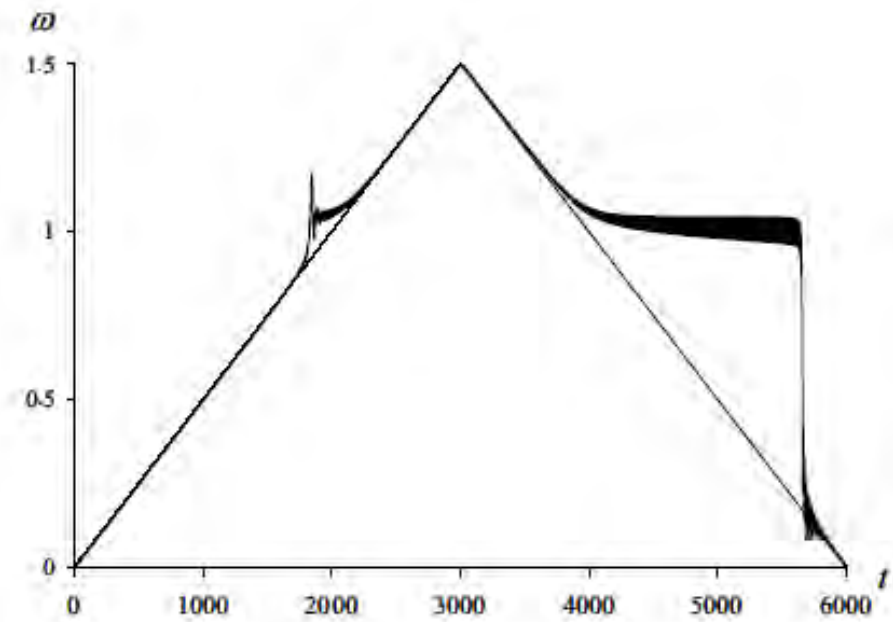
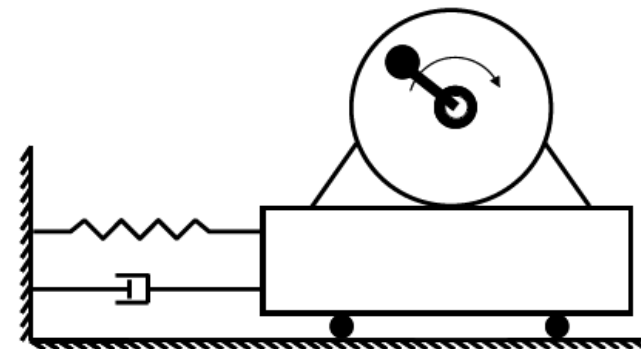
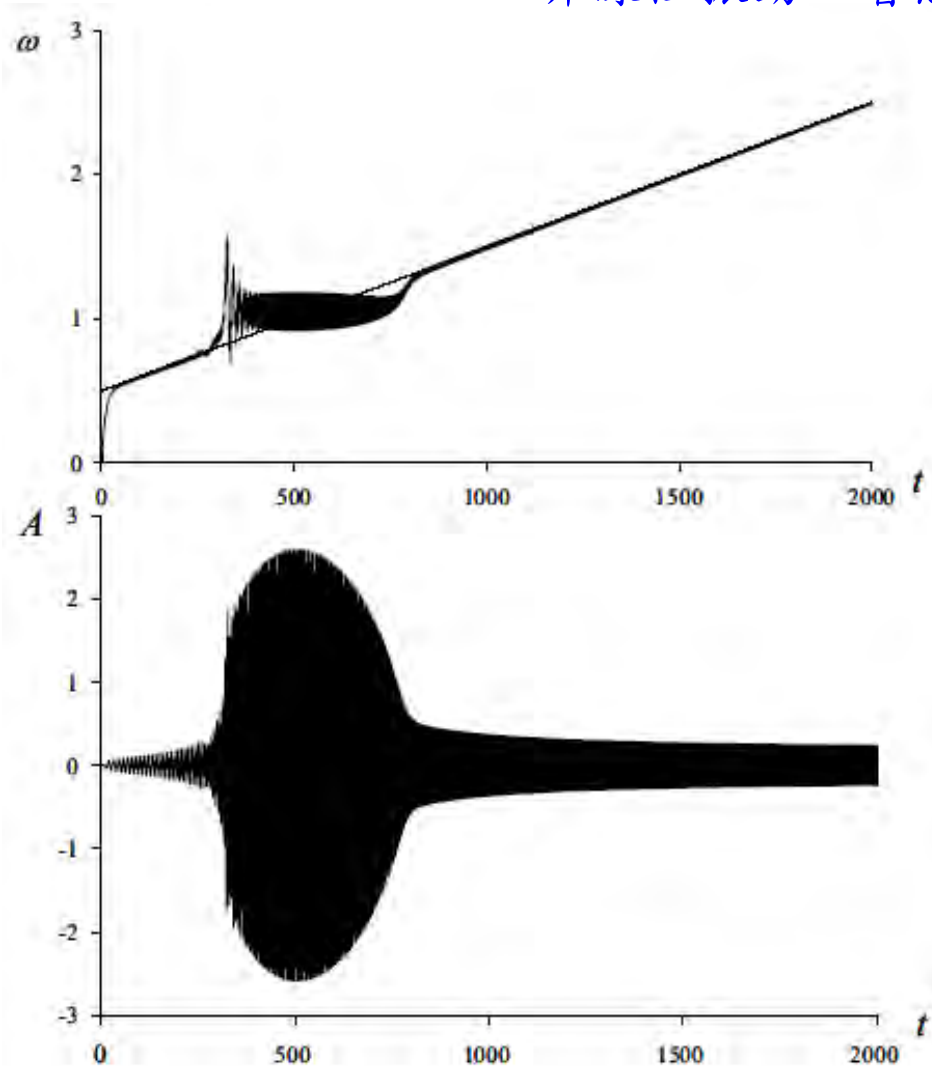
# 營運速度對系統穩定性之影響

20100429 : 營運速度 2.5 m/s



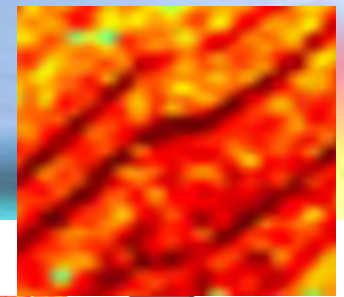
# 臨界轉速&共振頻率

非線性振動：暫態效應、鎖定共振

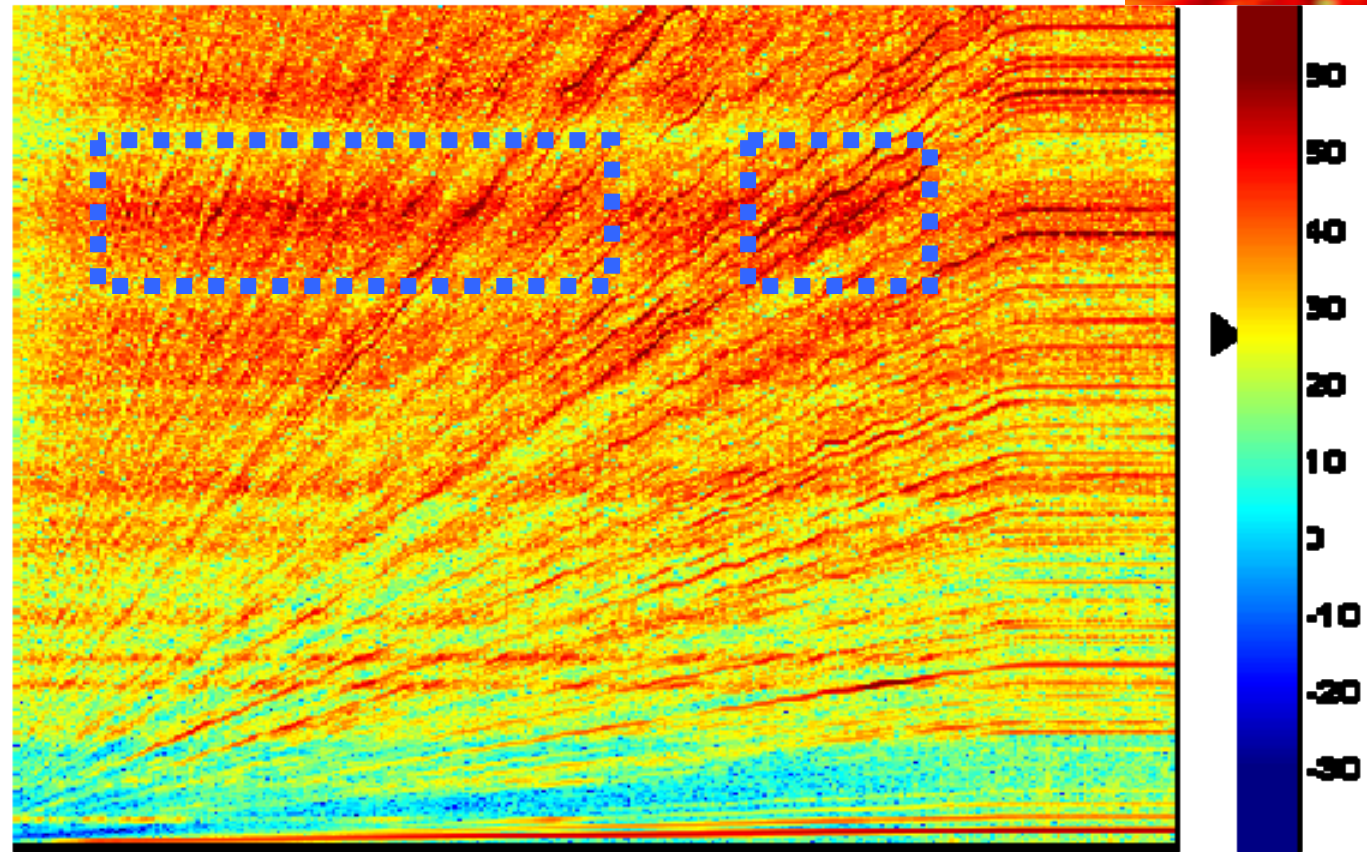
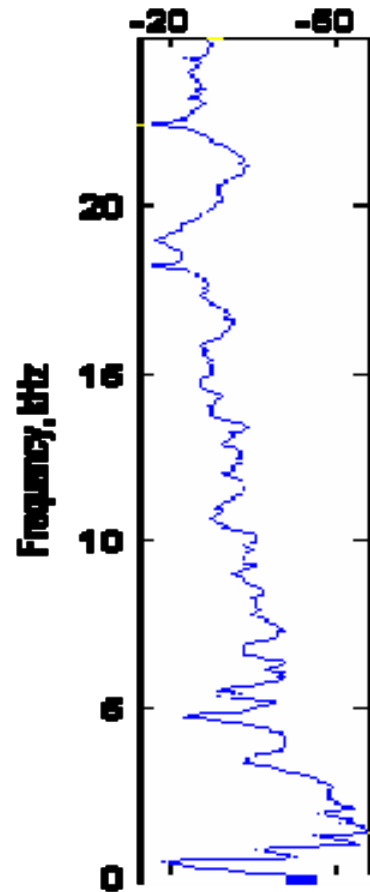




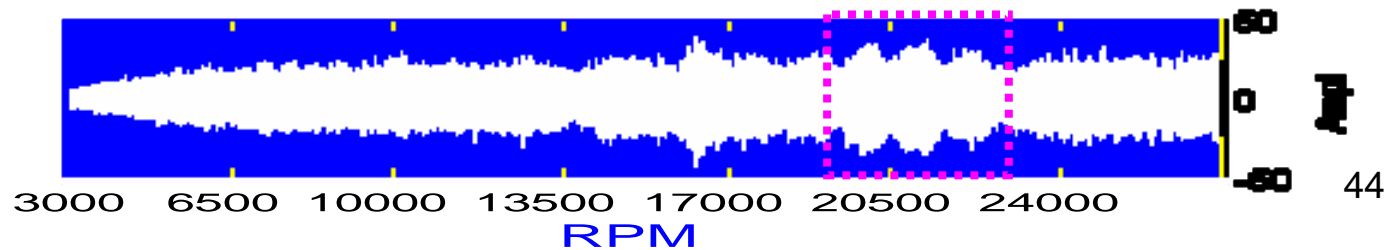
# 變轉速時頻分析：臨界轉速



變轉速時頻分析



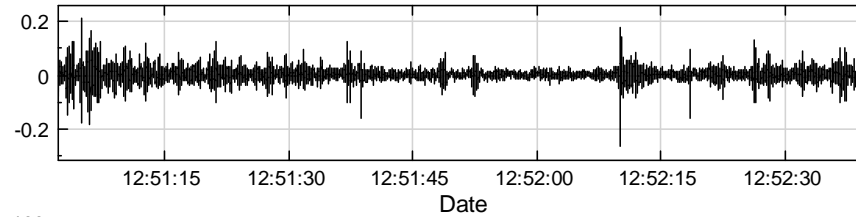
13.9674 secs  
0.0000 Hz  
26.7128 dB



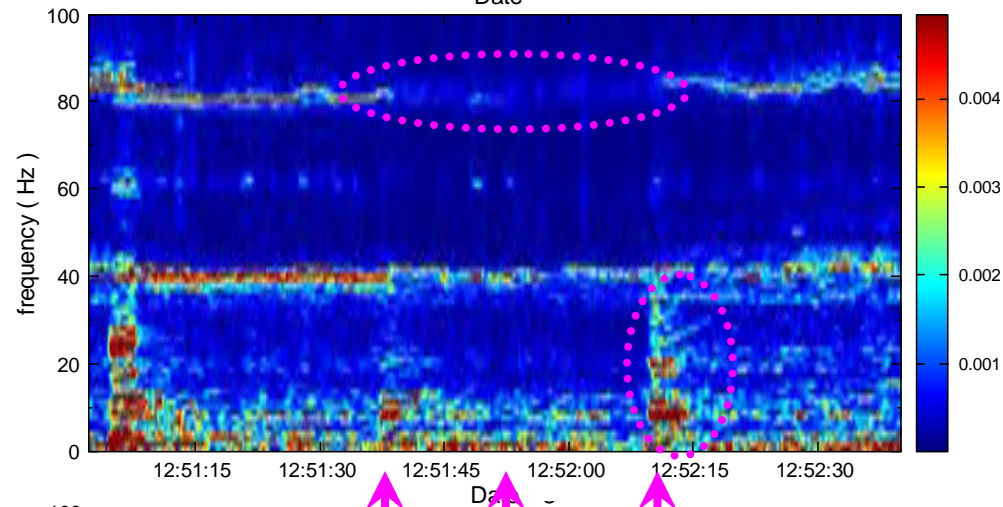


# T24⇒T23 (12:51:02)

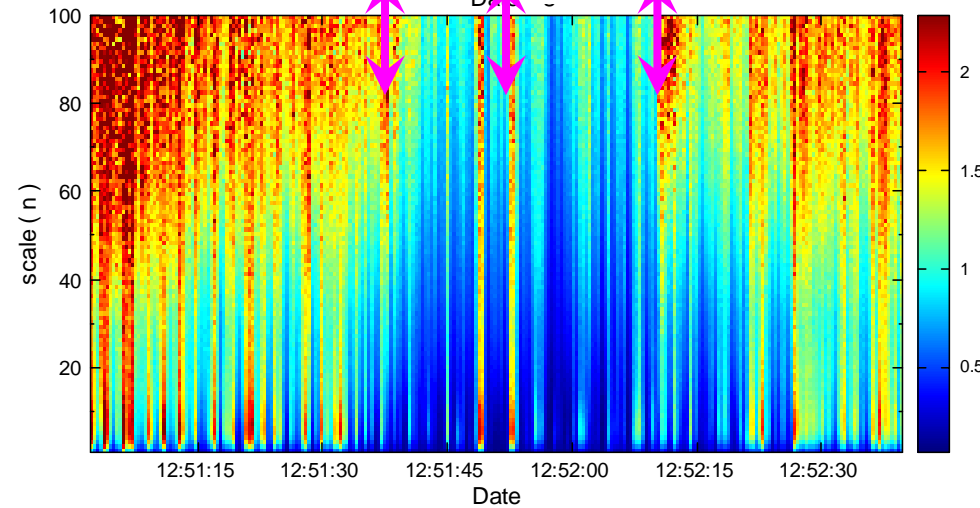
塔柱之間  
纜車振動



纜車振動  
時頻圖



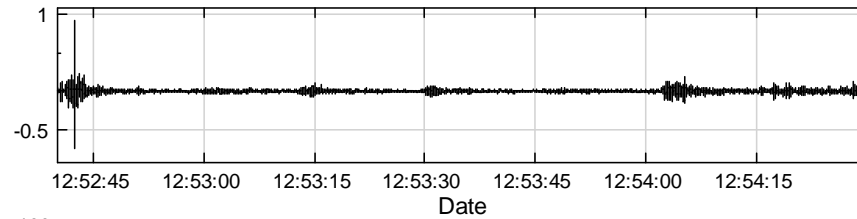
纜車振動  
MSE  
(軟體判別)



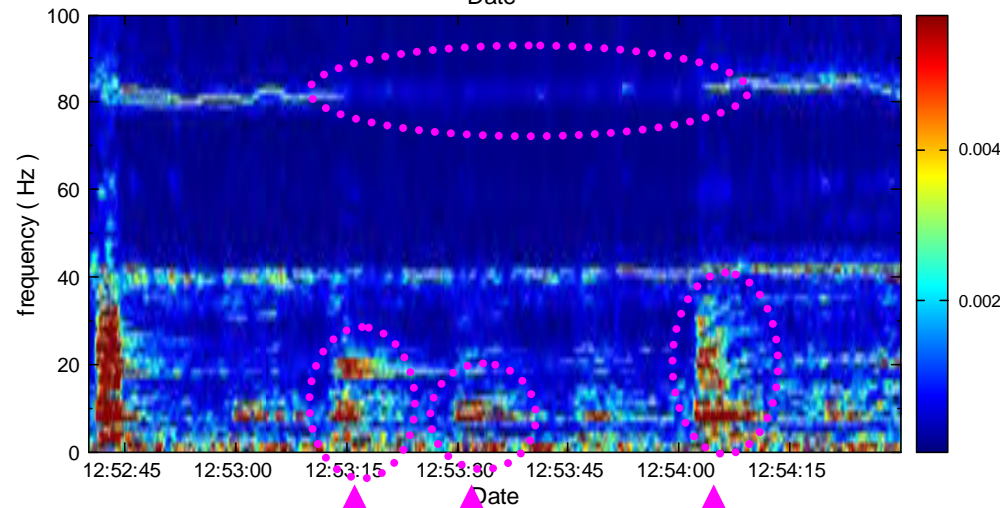
明顯異常  
振動之紀錄時間點  
(人工判別)

# T23⇒T22 (12:52:40)

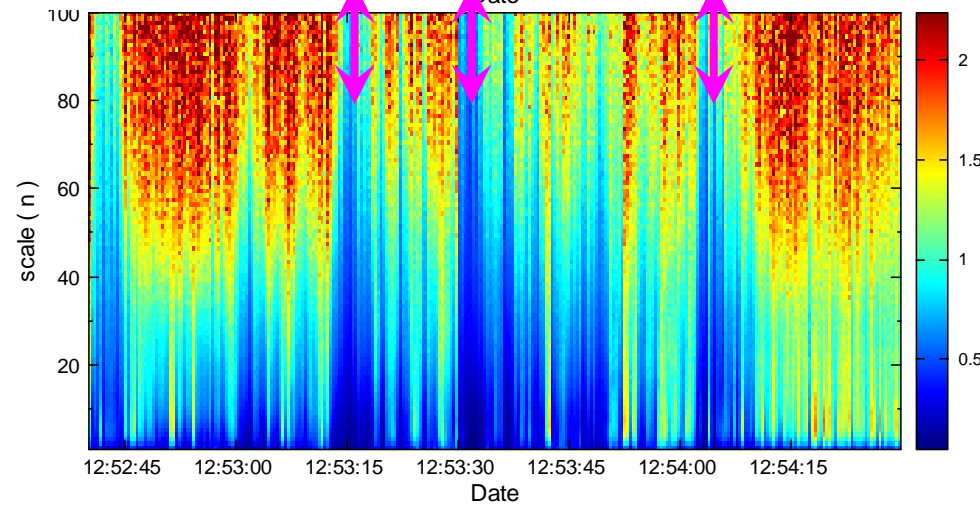
塔柱之間  
纜車振動



纜車振動  
時頻圖



纜車振動  
MSE  
(軟體判別)



明顯異常  
振動之紀錄時間點  
(人工判別)



# 工具機變速齒輪機箱振噪檢測

# 量測設置

轉盤轉速



轉盤端加速度



聲壓

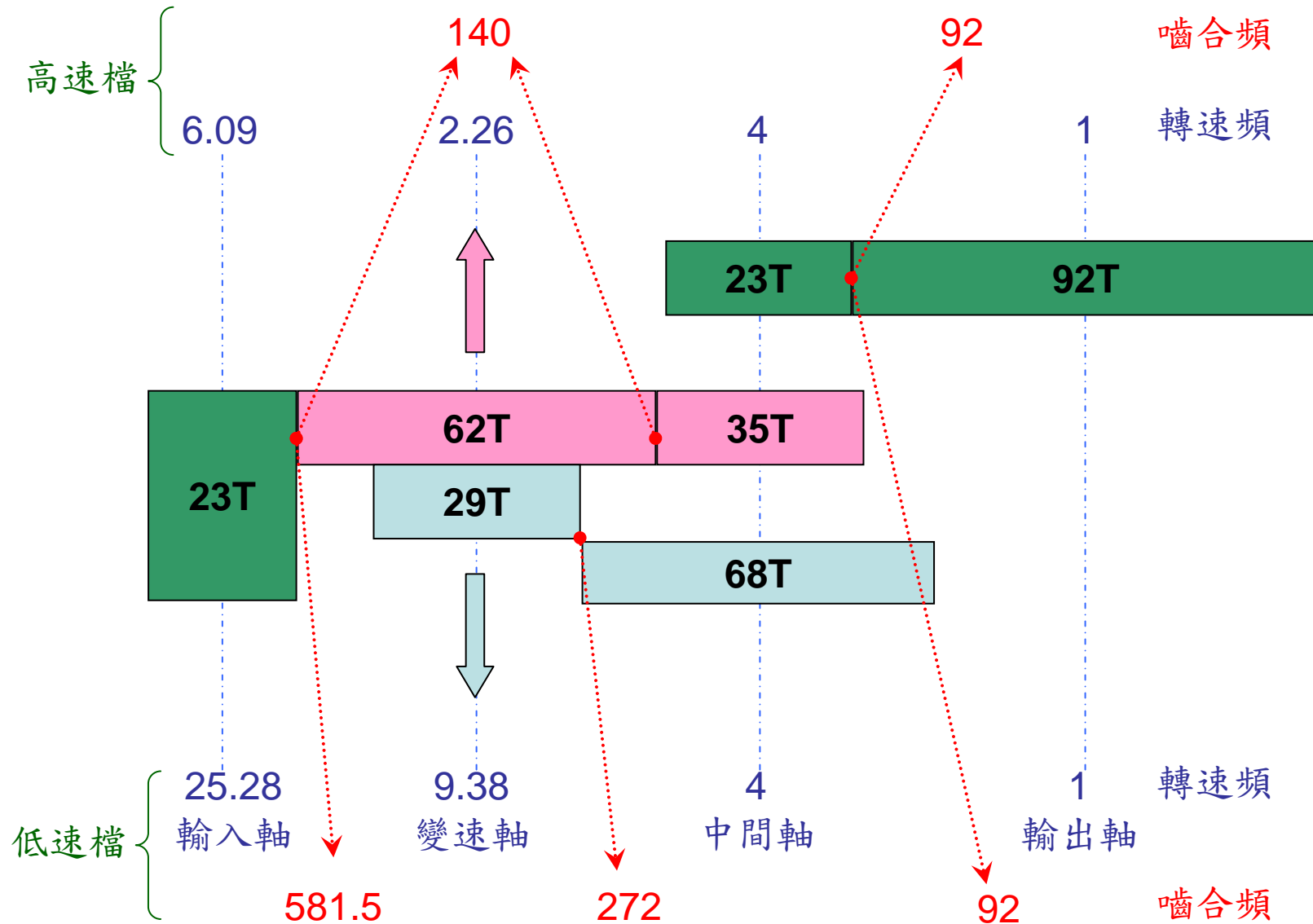


馬達端加速度

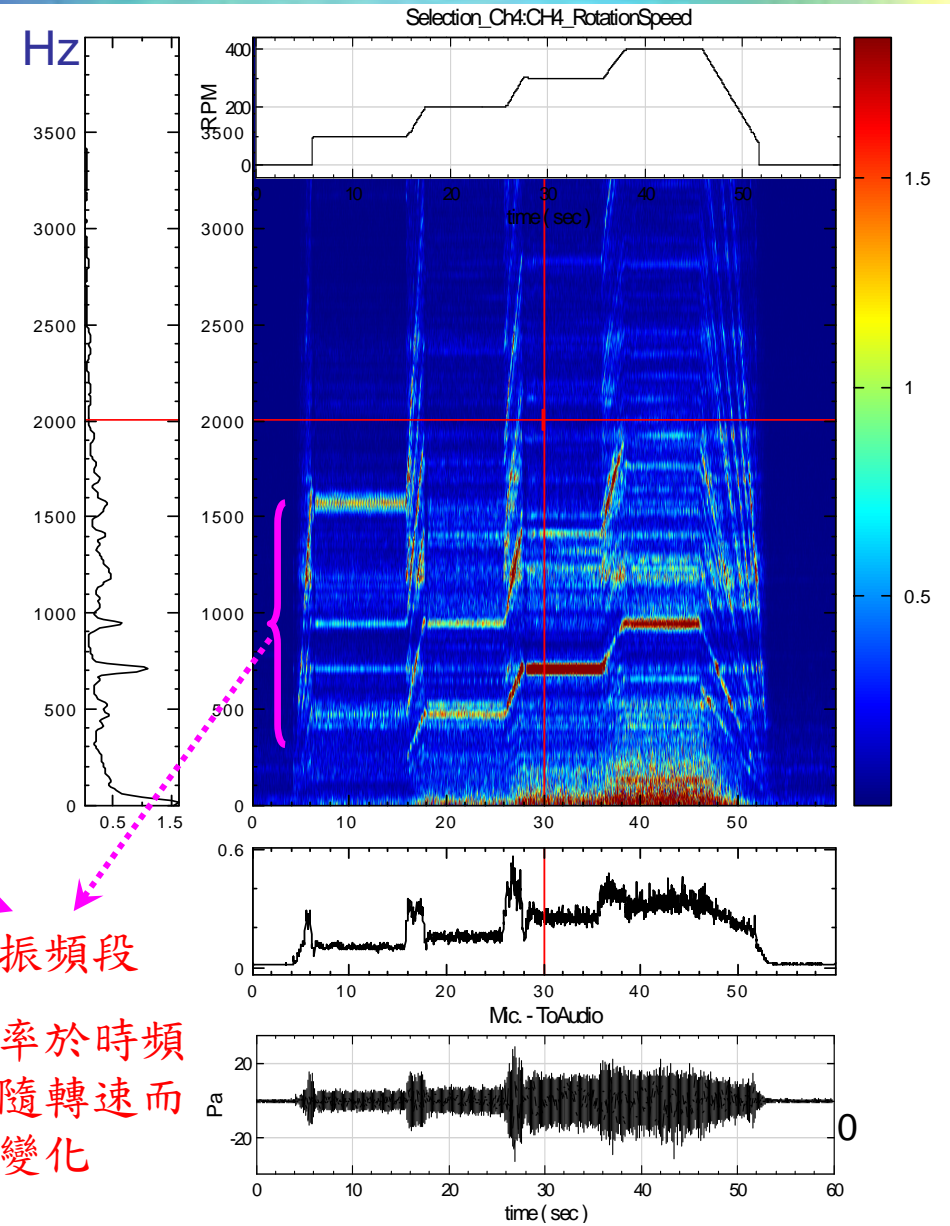
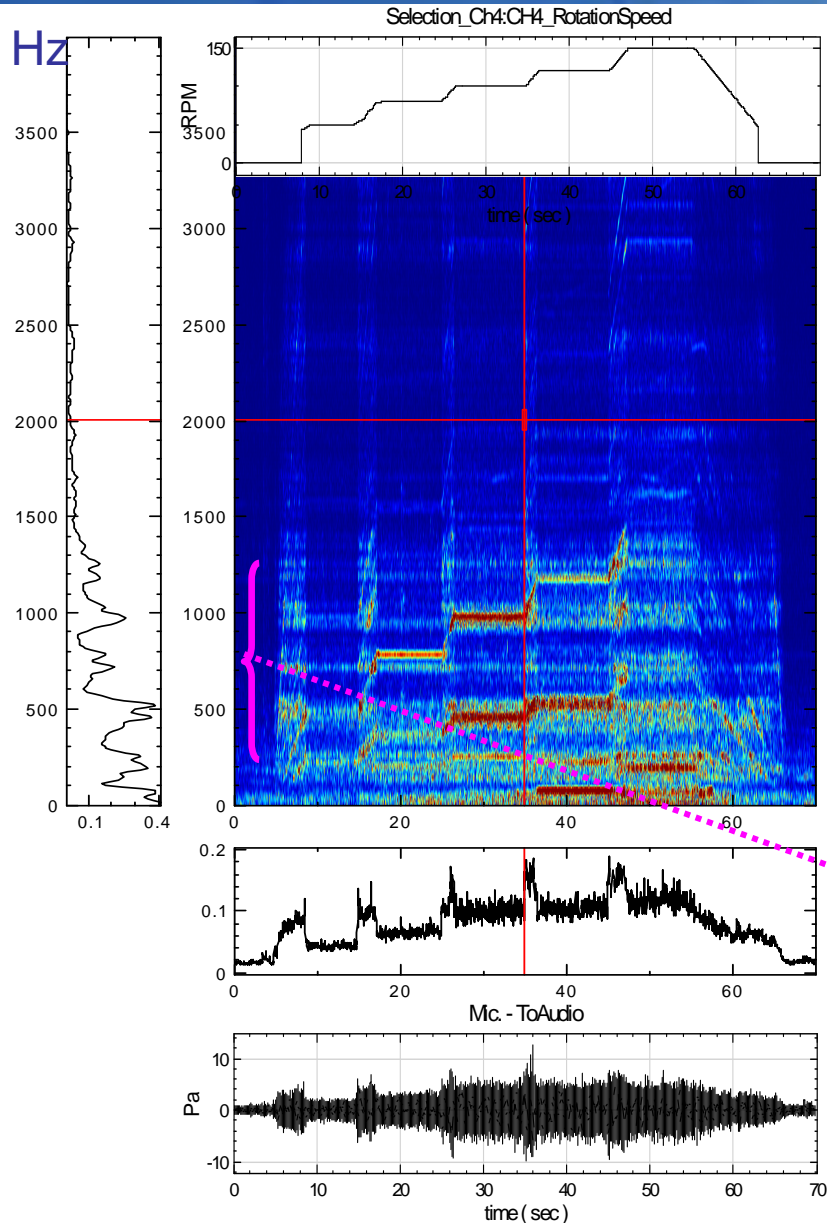




# 轉速頻與嚙合頻：以轉盤轉速為基準



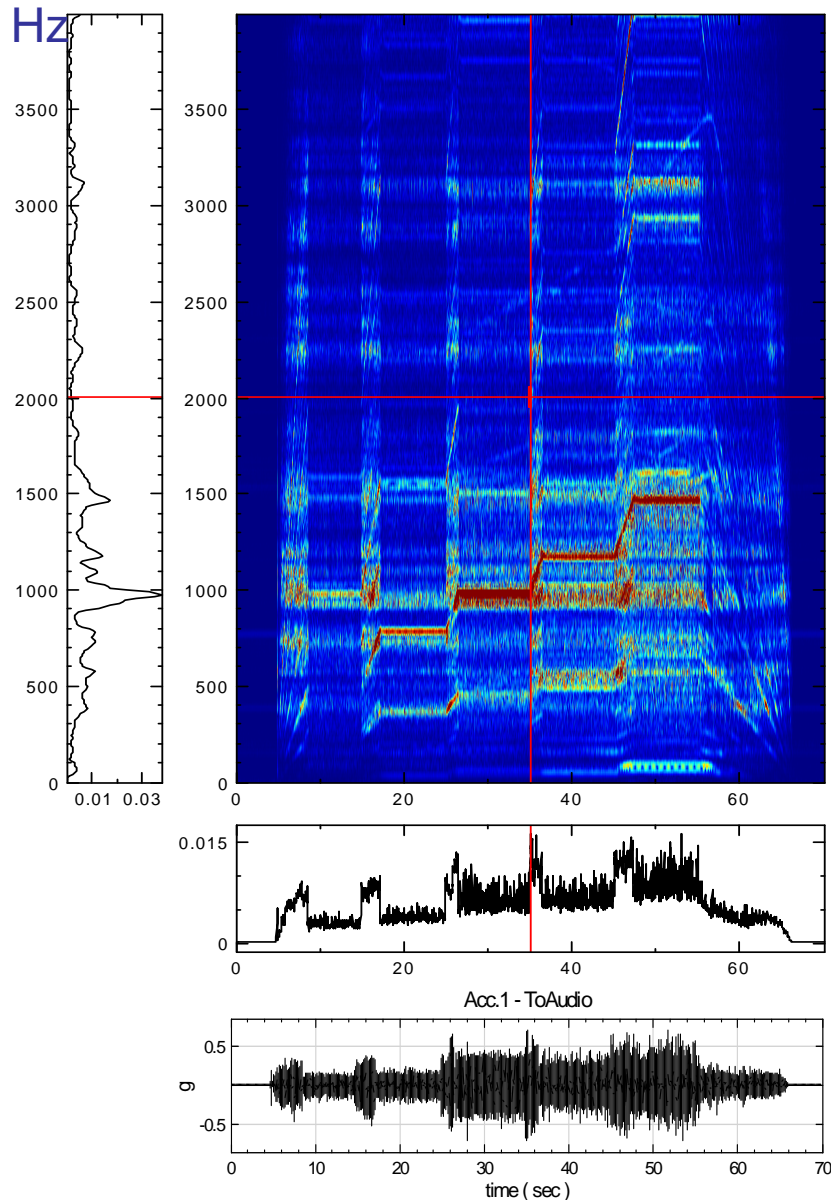
# 聲壓時頻圖：低檔VS.高檔



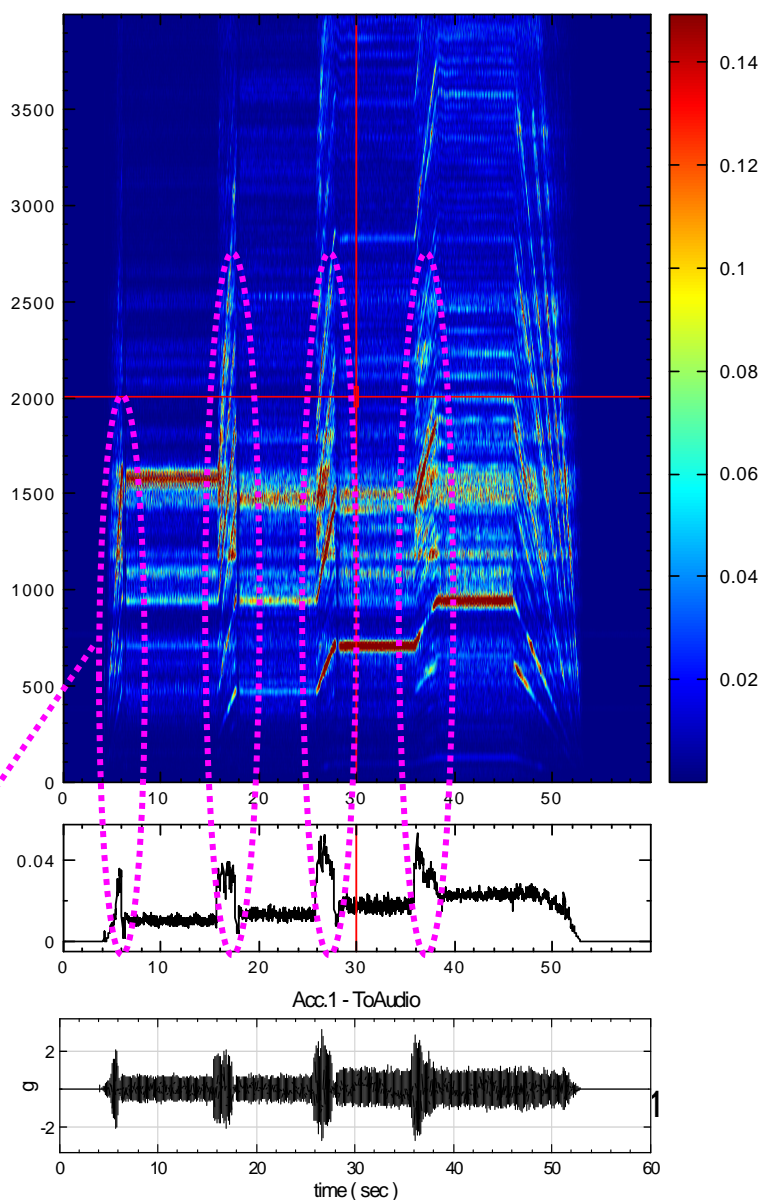
共振頻段

其頻率於時頻圖  
不隨轉速而  
變化

# 轉盤端加速度時頻圖：低檔VS.高檔



加速激發  
共振



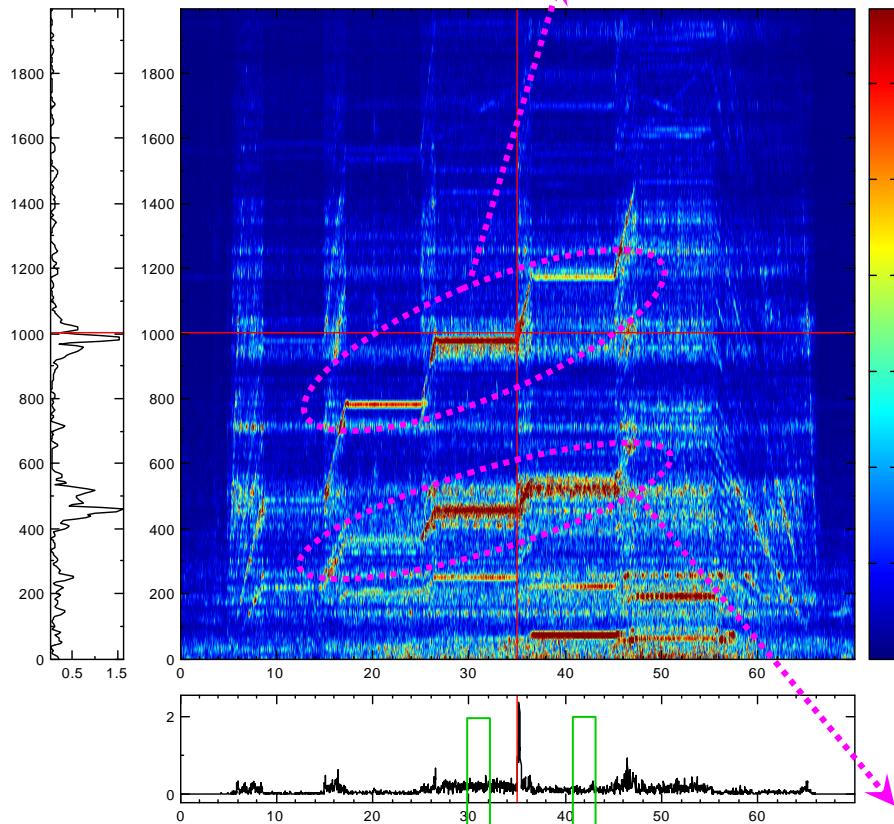


# 低檔聲壓：頻率vs.輸出軸轉速階次

輸入軸嚙合頻

輸出軸轉速之581.5倍頻

Hz

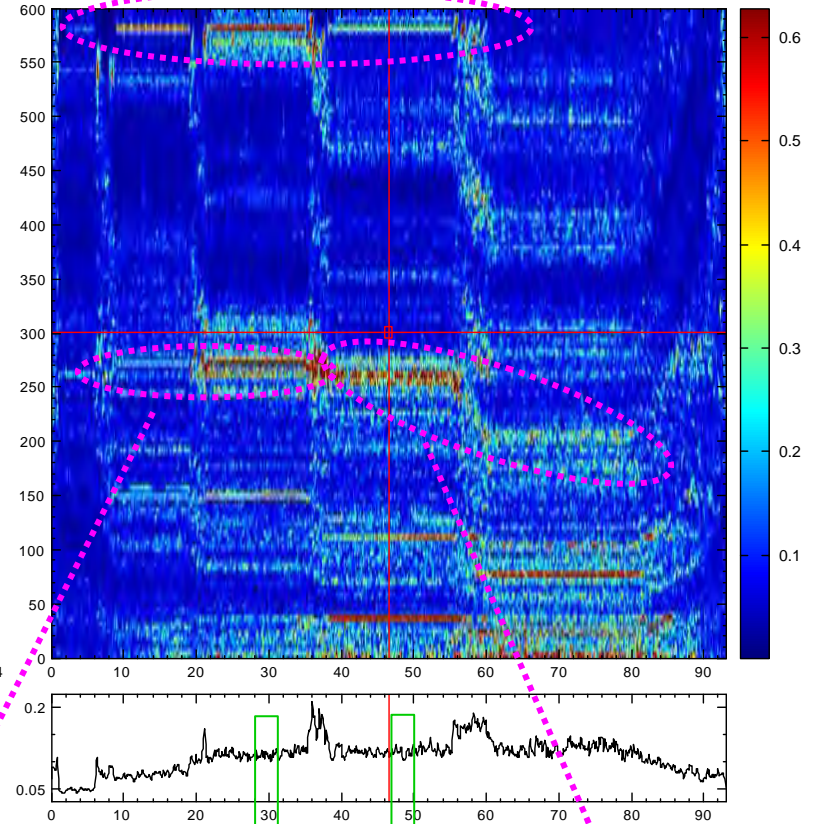


100RPM 150RPM

中間軸嚙合頻

272倍頻

Order



100RPM 150RPM

共振音

52

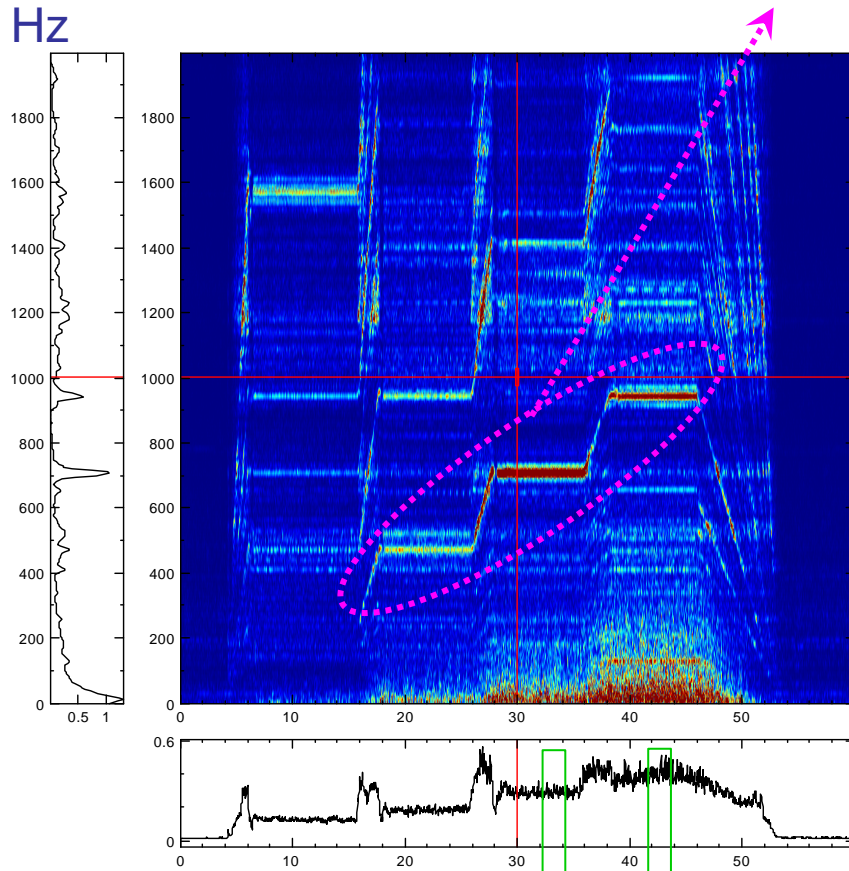


# 高檔聲壓：頻率vs.輸出軸轉速階次

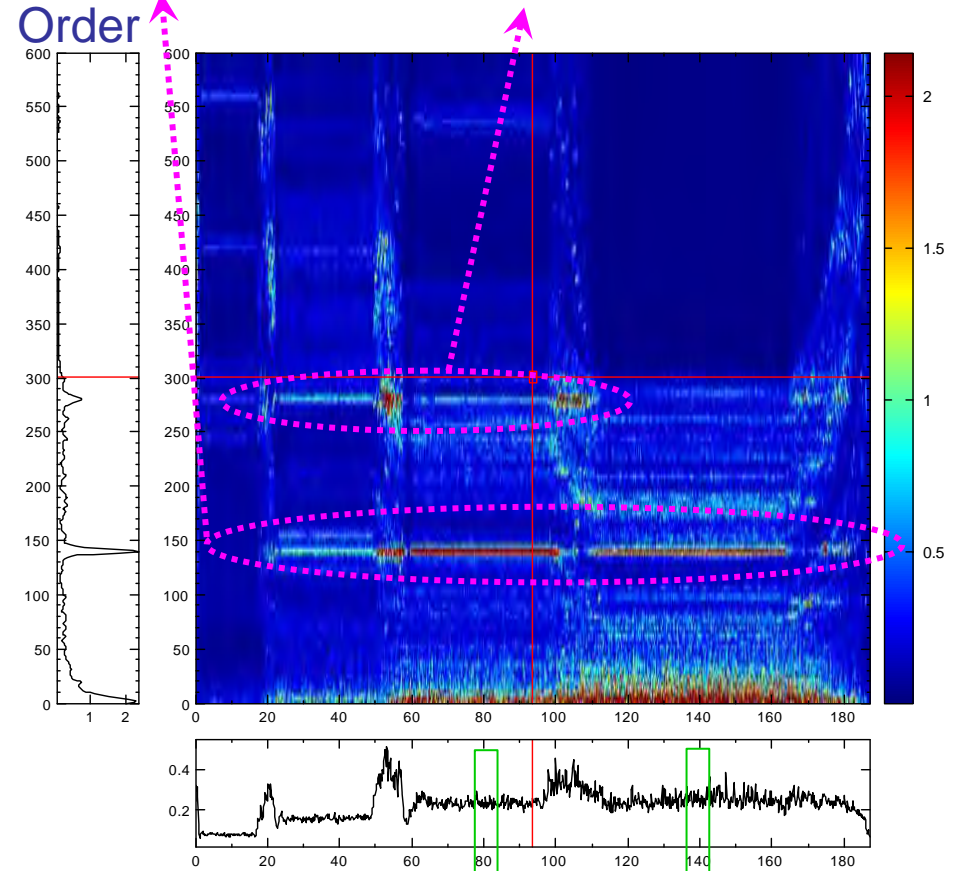
輸入軸&中間軸嚙合頻

輸出軸轉速之140倍頻

輸入軸&中間軸嚙合頻之二倍頻



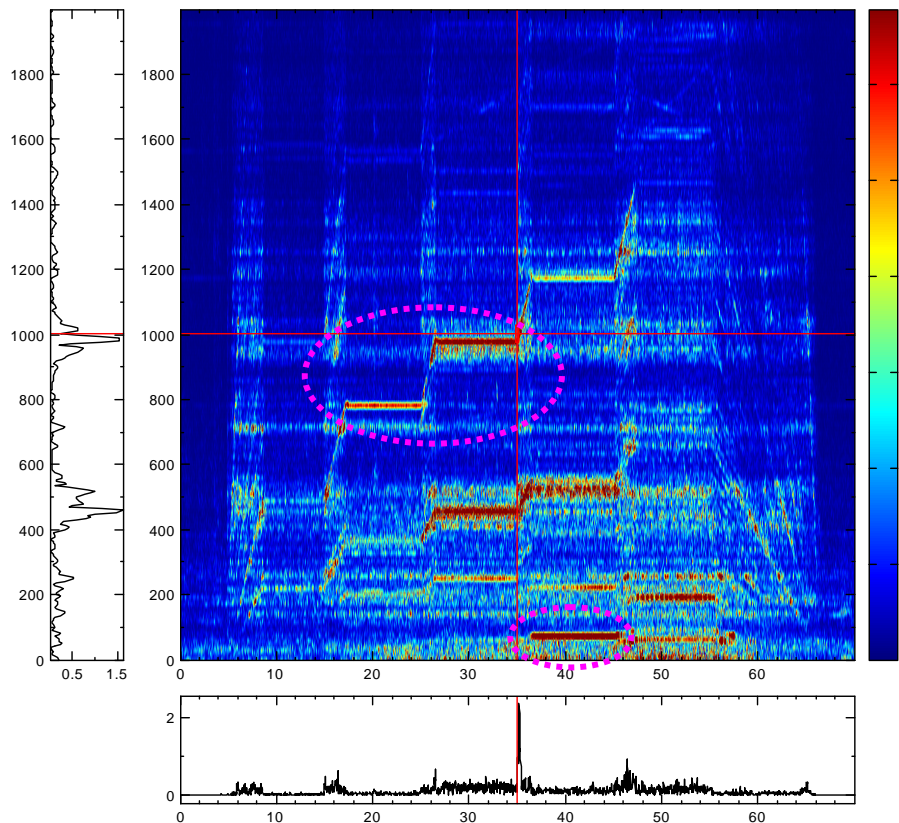
300RPM 400RPM



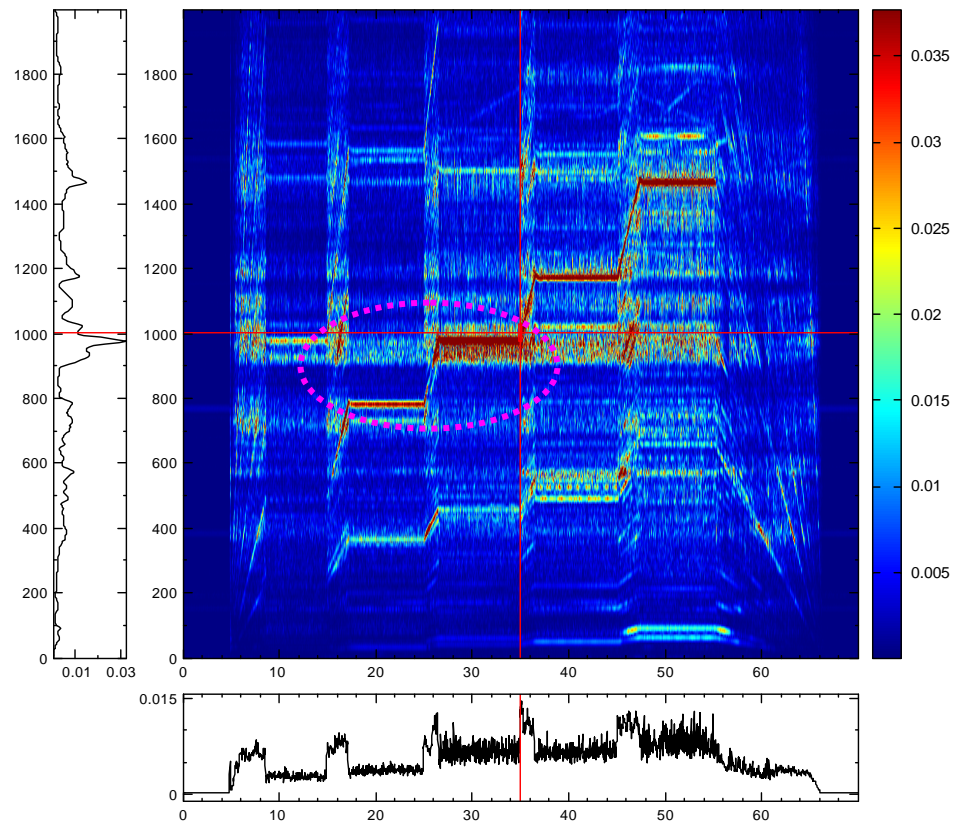
300RPM 400RPM

# 低檔時頻圖：聲壓VS.轉盤端加速度

Hz



Hz



噪音

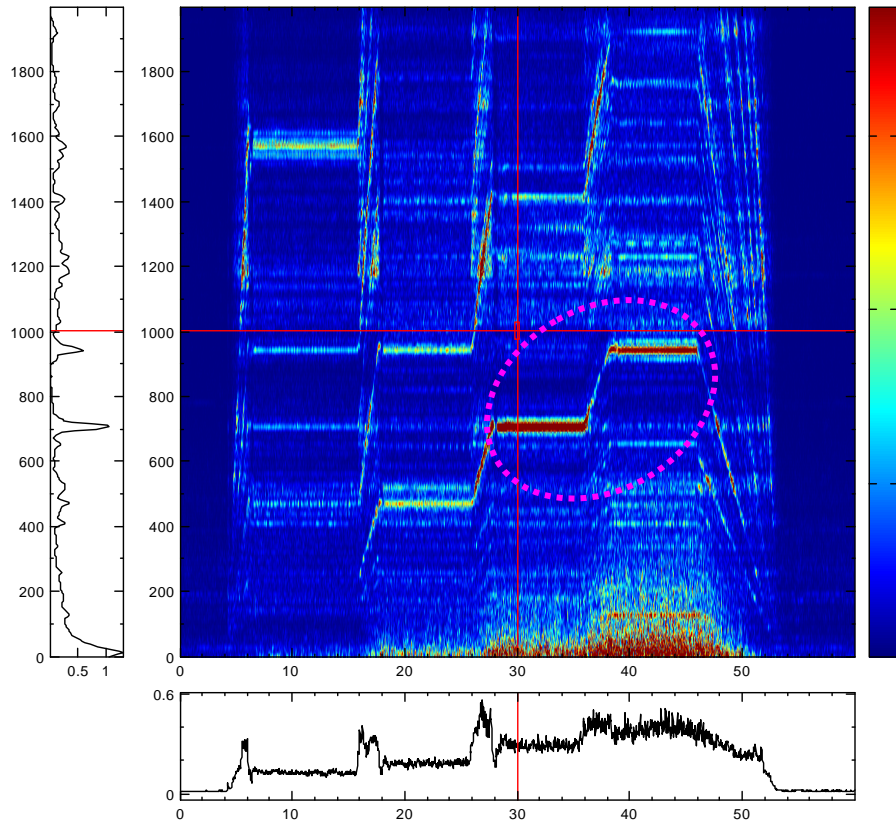


振動

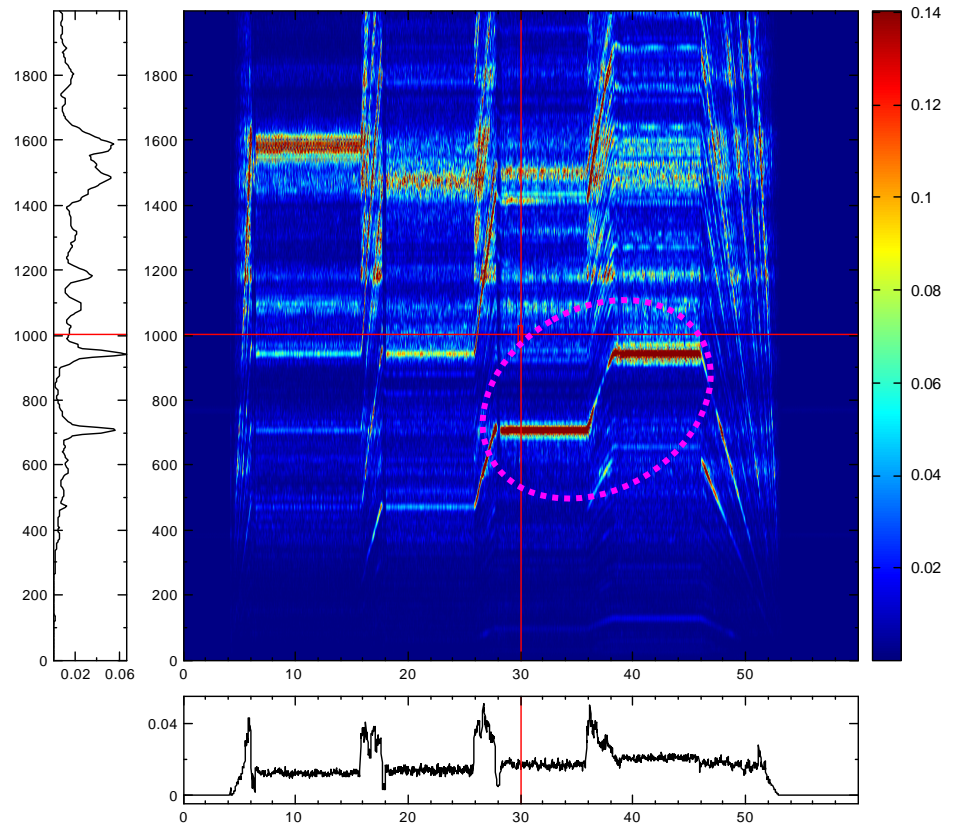


# 高檔時頻圖：聲壓VS.轉盤端加速度

Hz



Hz

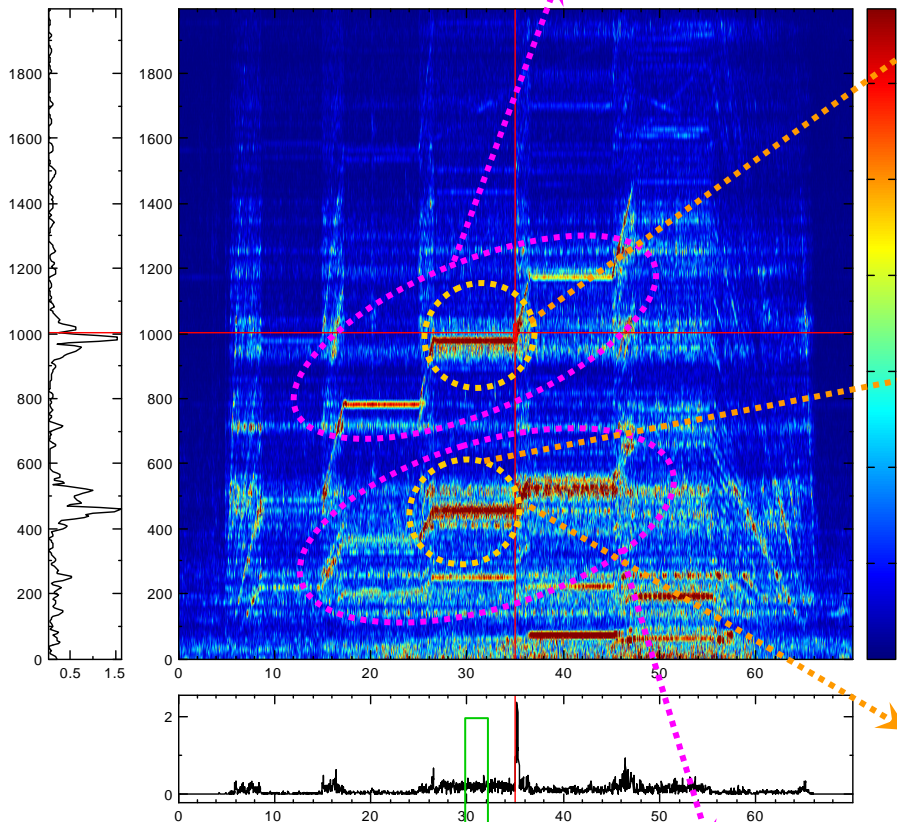


噪音 ← 振動

# 低速檔聲壓異常：嚙合頻之調幅頻率

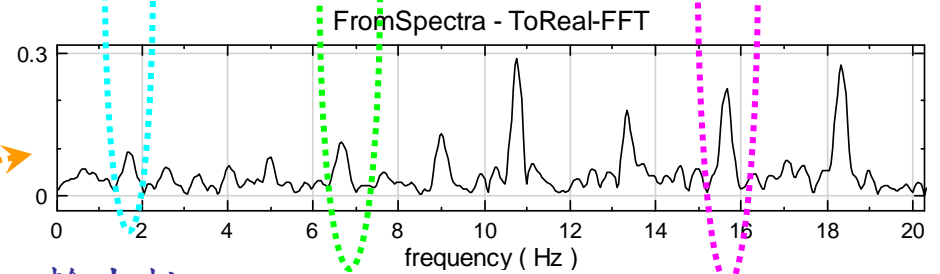
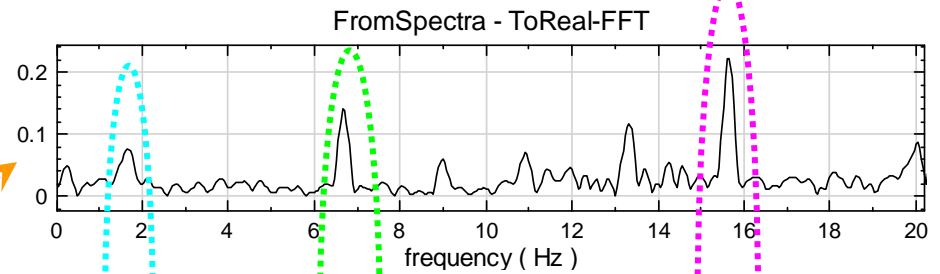
輸入軸嚙合頻  
輸出軸轉速之581.5倍頻

Hz



100RPM

中間軸嚙合頻  
272倍頻

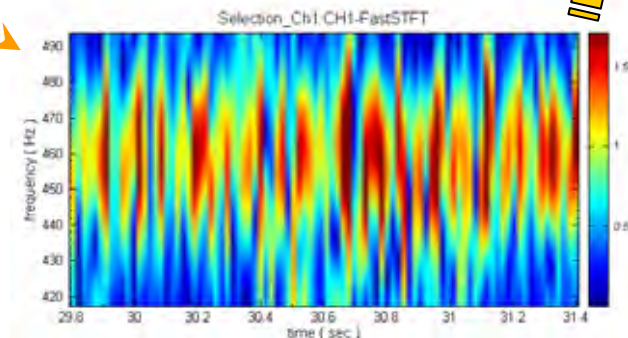


輸出軸  
轉速頻  
率1X

中間軸轉速  
頻率1X

變速軸轉速  
頻率1X

FFT

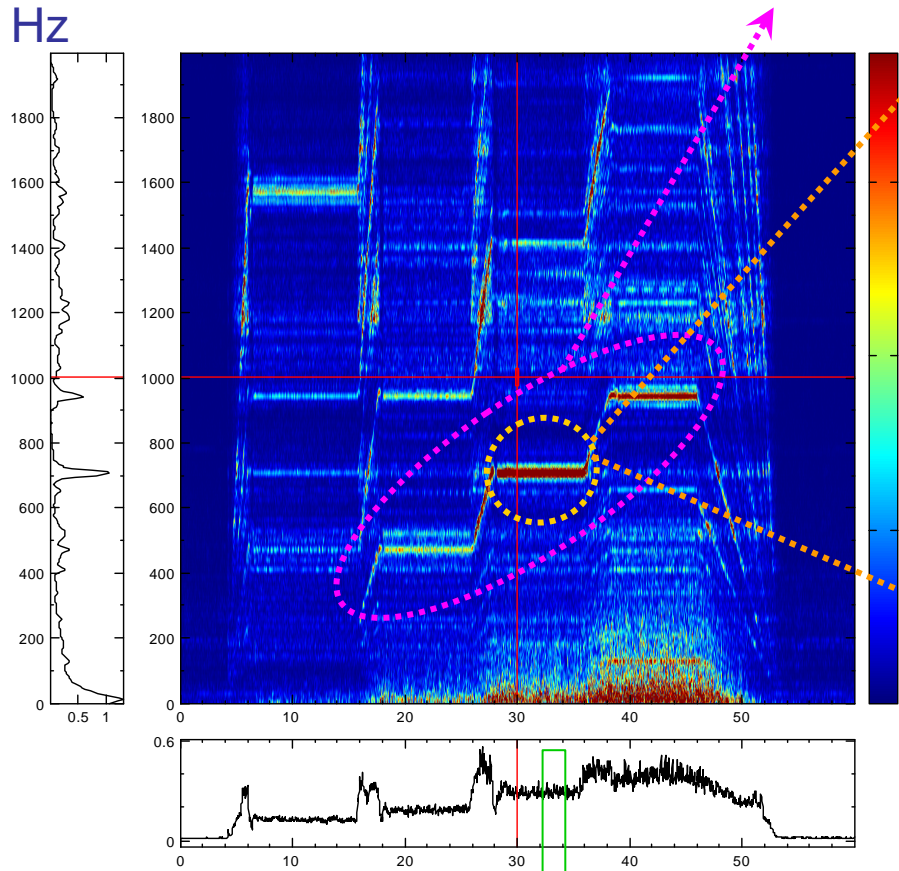


主要異常為  
變速軸偏心

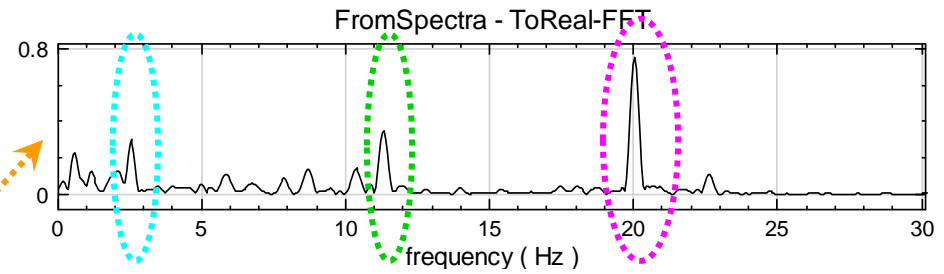


# 高速檔聲壓異常：嚙合頻之調幅頻率

輸入軸 & 中間軸嚙合頻  
輸出軸轉速之140倍頻



300RPM



輸出軸  
轉速頻  
率1X

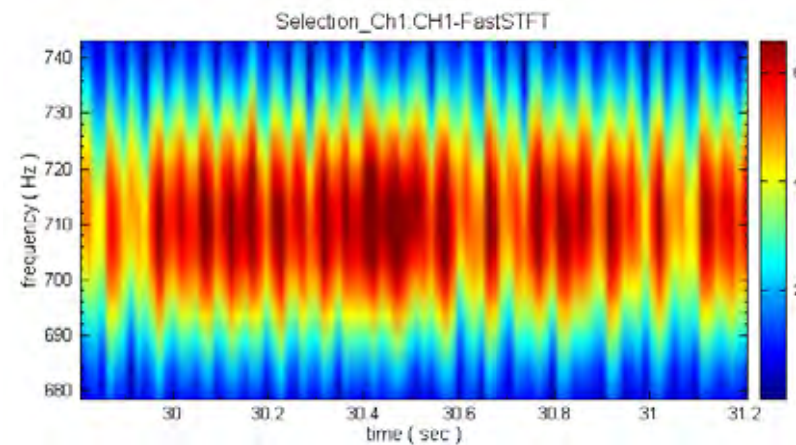
變速軸  
轉速頻  
率1X

中間軸  
轉速頻  
率1X



FFT

主要異常為中間軸偏心

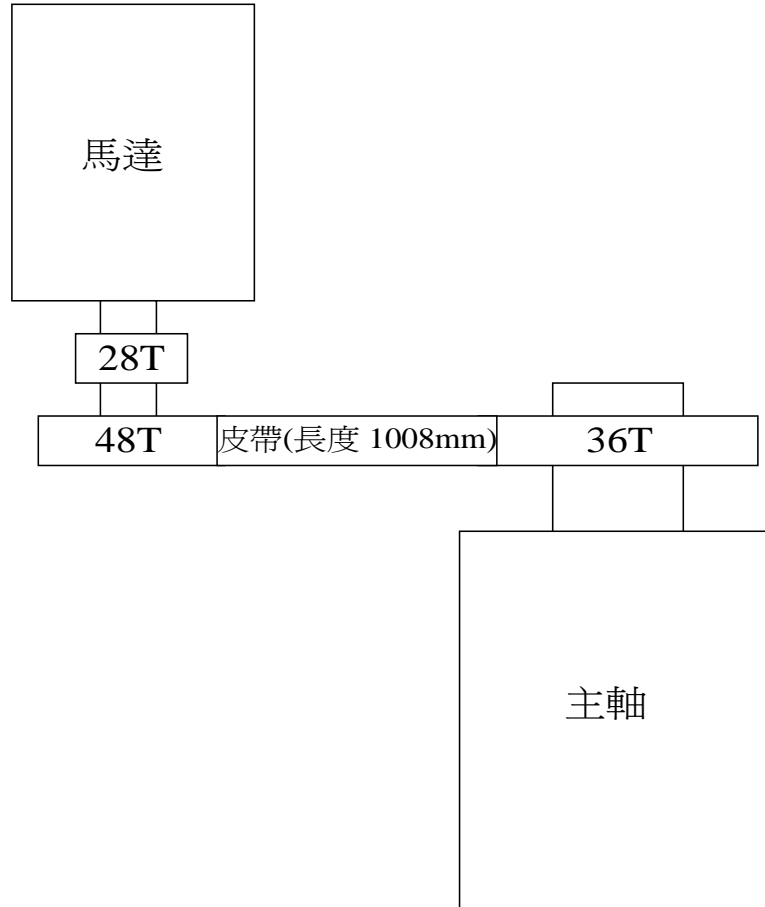




# 皮帶式主軸異音檢測異音檢測

# 皮帶式主軸示意圖

馬達轉速頻率：50 → 60 → 70 → 80 → 90 → 100 Hz

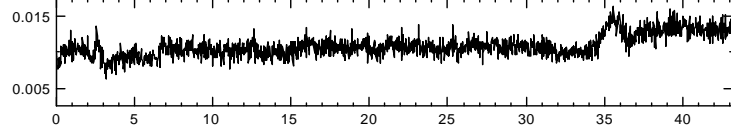
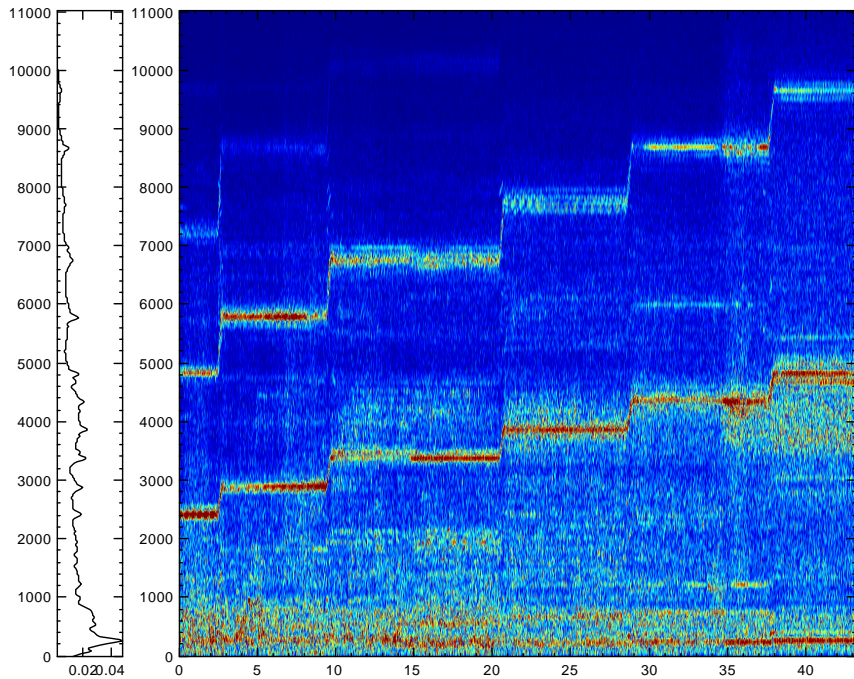


主軸轉速頻率：66.67 → 80 → 93.33 → 106.67 → 120 → 133.33 Hz

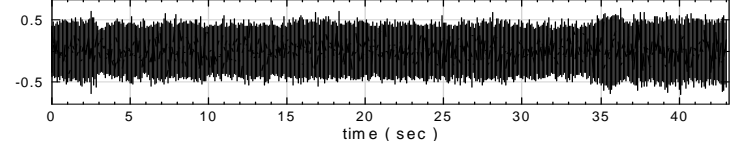
主軸轉速RPM：4000 → 4800 → 5600 → 6400 → 7200 → 8000 RPM<sup>59</sup>



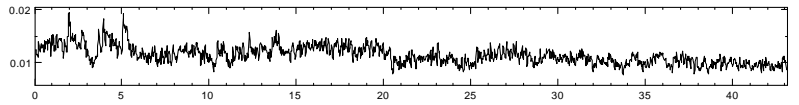
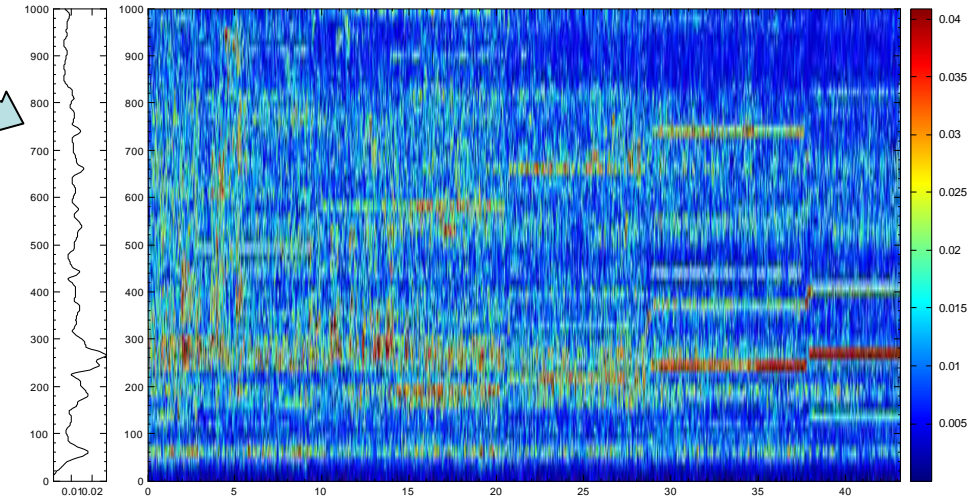
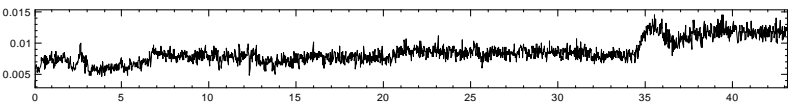
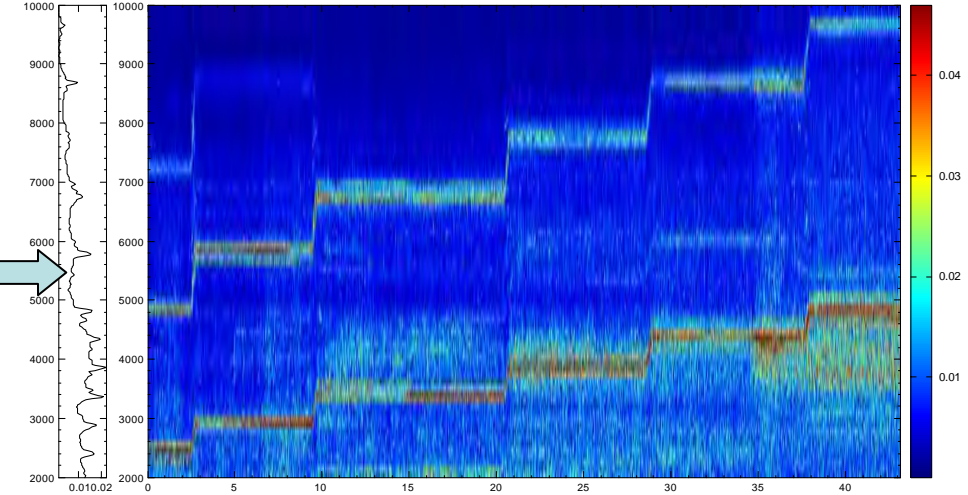
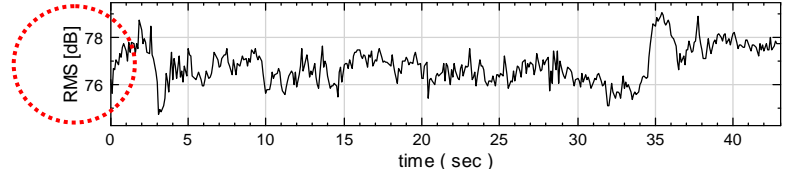
# 聲音檔時頻分析



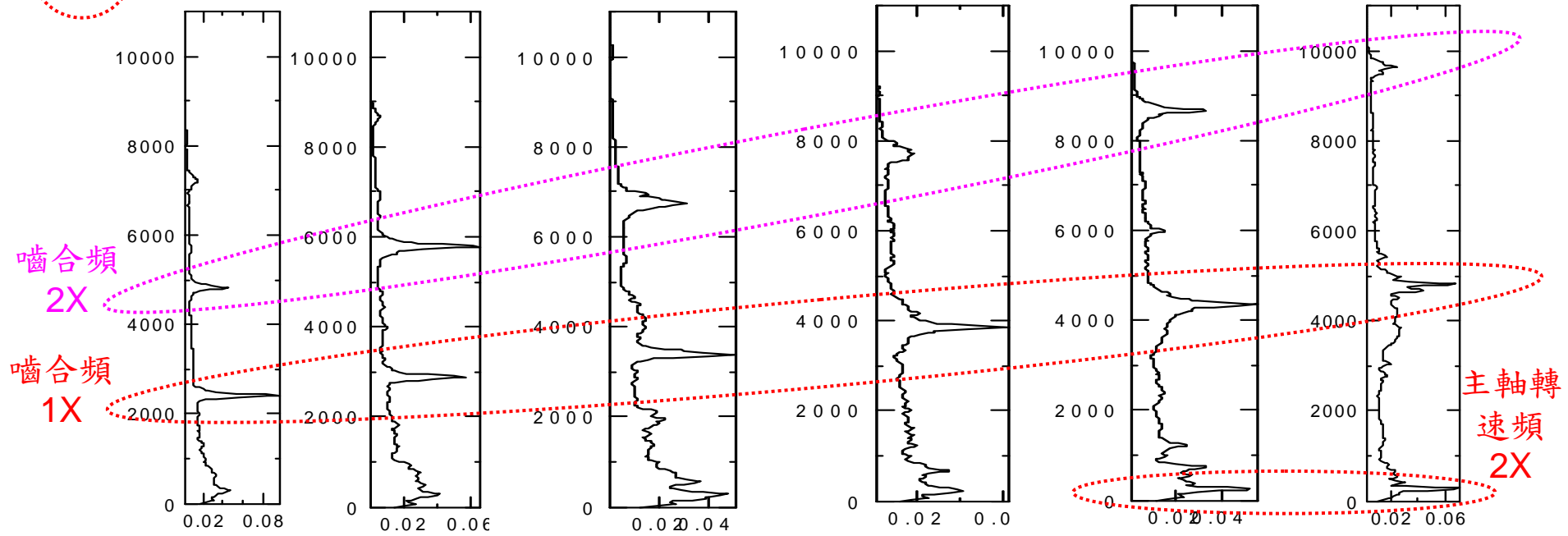
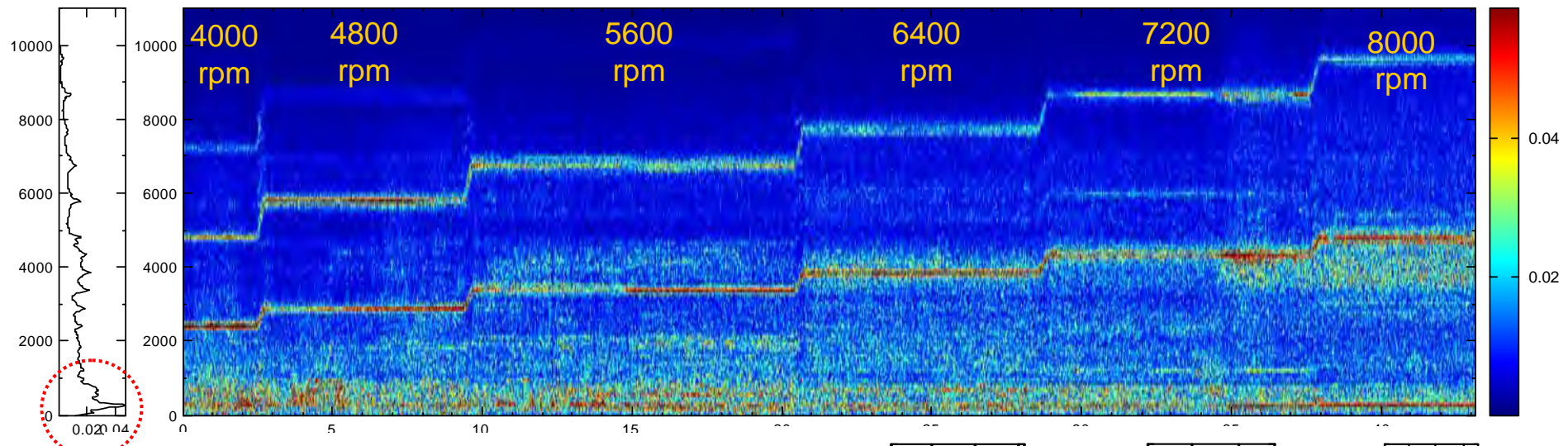
永進齒輪箱噪音量測-22050Hz\_Ch1:CH1



永進齒輪箱噪音量測-22050Hz\_Ch1:CH1-RMS



# 各轉速之異音頻譜比較





# 嚙合頻段異音頻譜

4000  
rpm

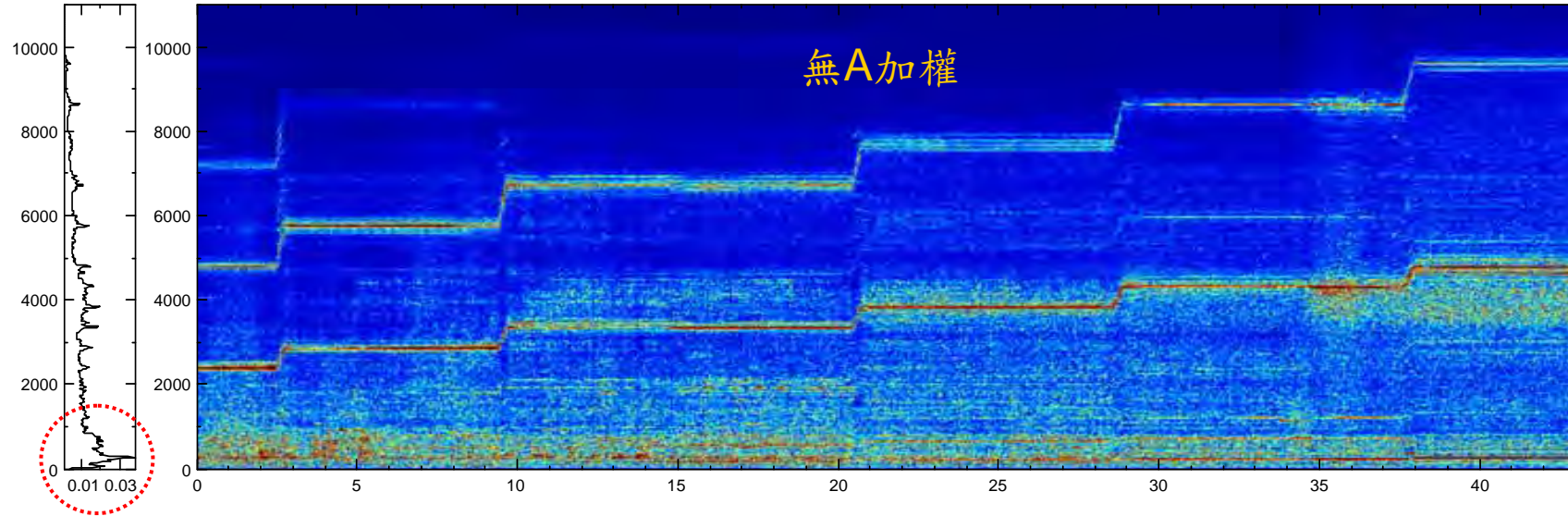
4800  
rpm

5600  
rpm

6400  
rpm

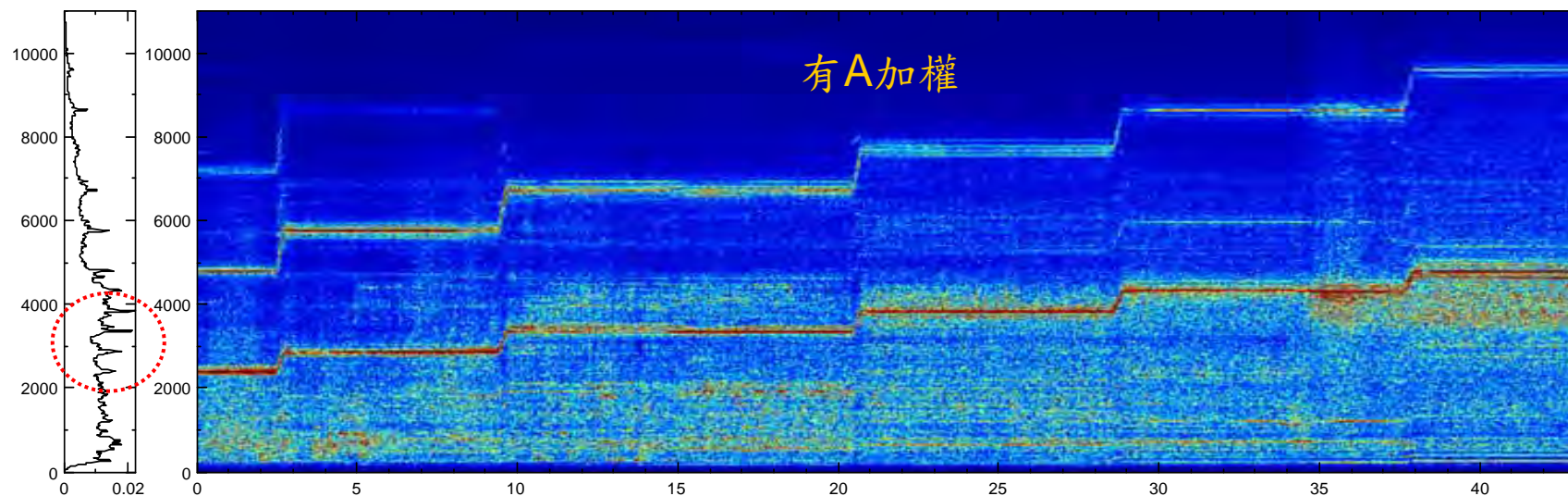
7200  
rpm

8000  
rpm



共振或  
共鳴之  
頻段

主軸2X



人耳主  
要感受  
嚙合頻  
1X

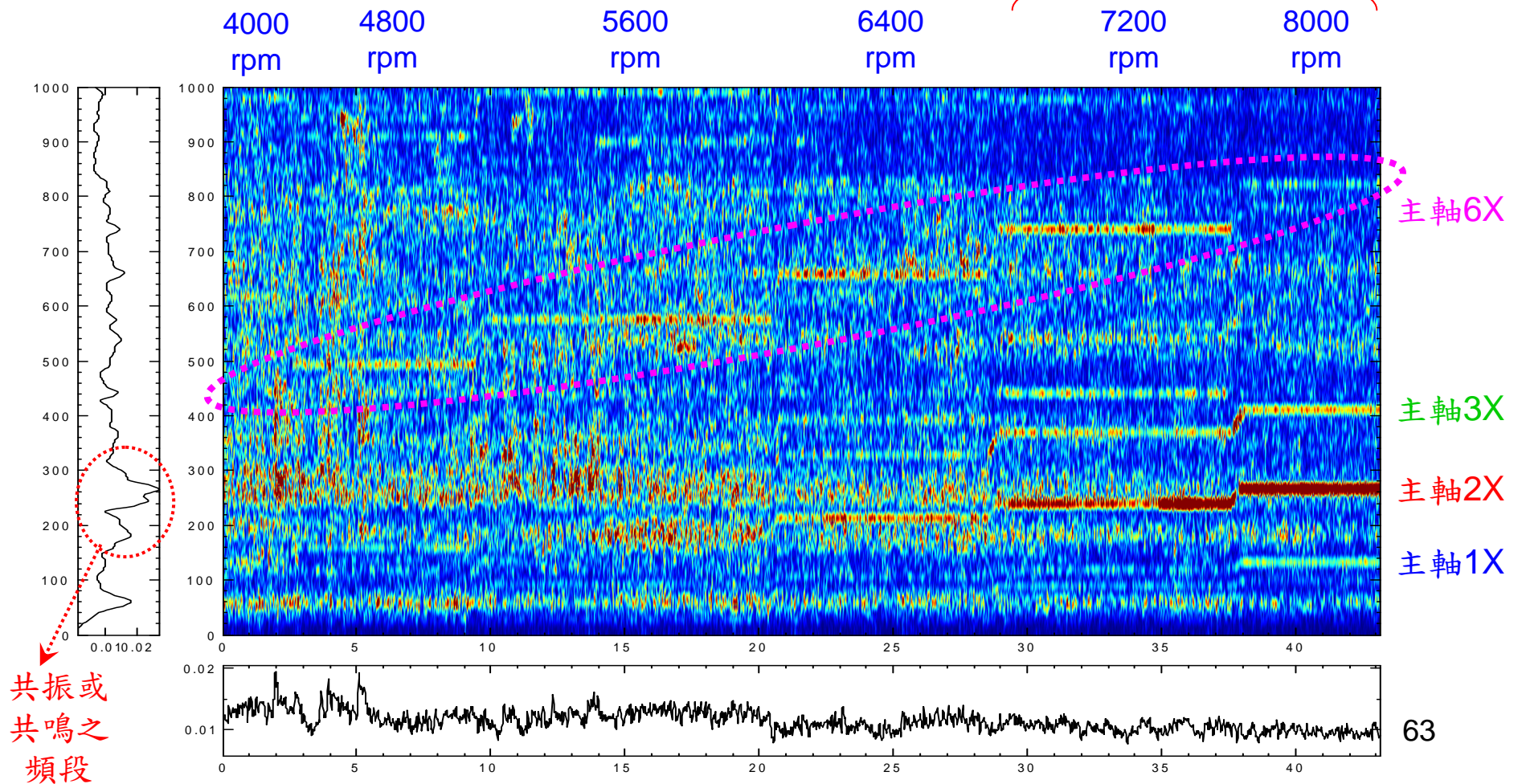
62



# 主軸轉速頻段異音頻譜

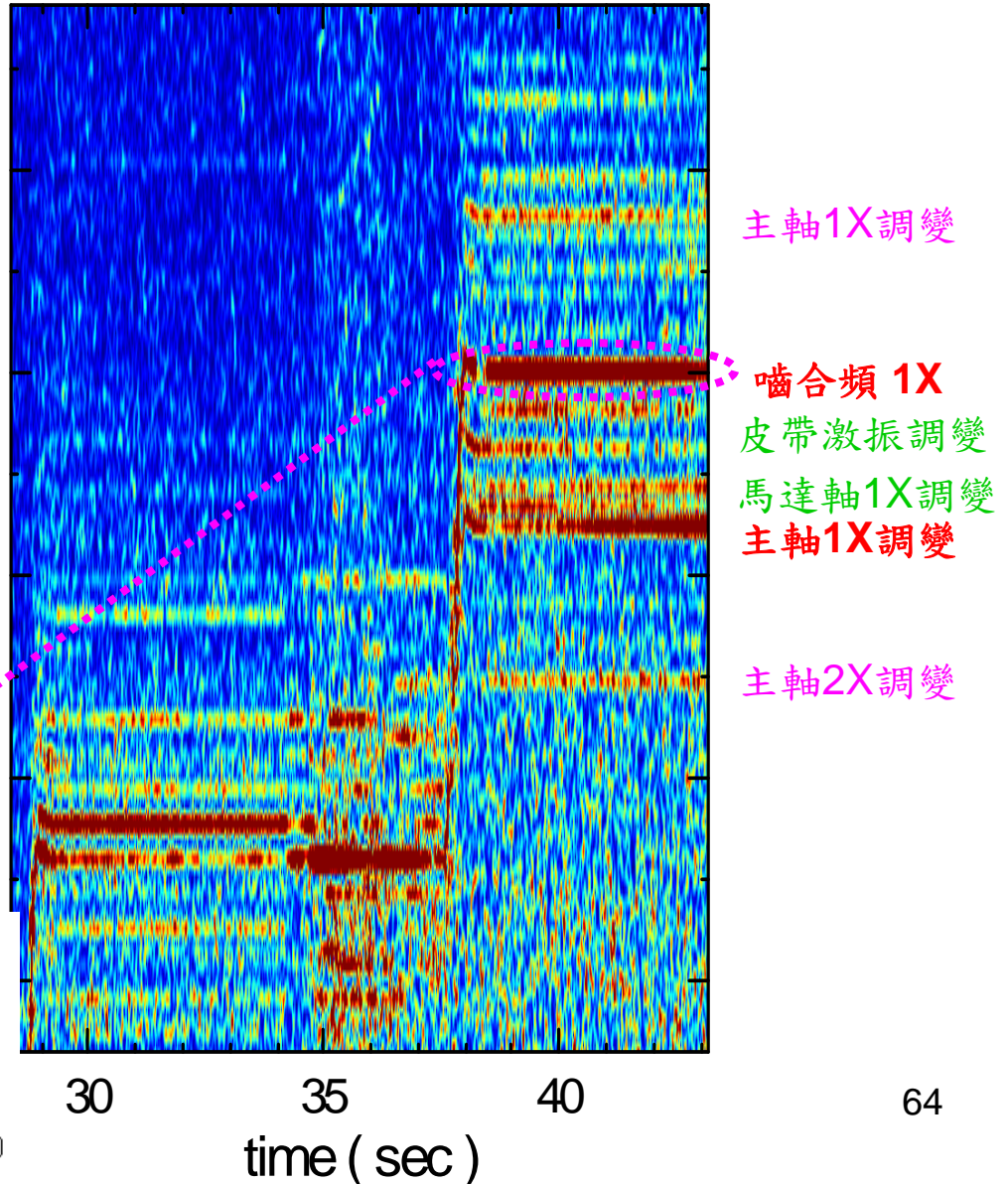
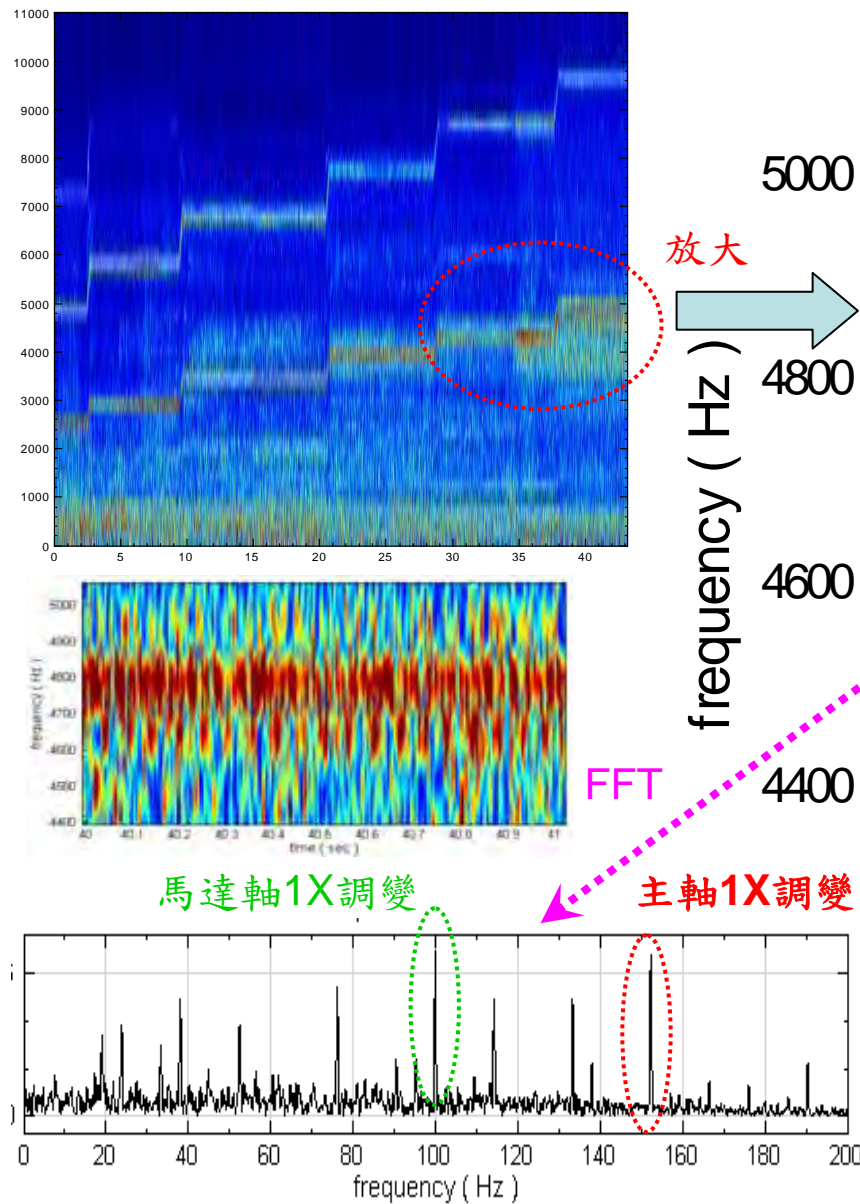
主要異常：主軸對心問題

主軸轉速頻率2X





# 嚙合頻率受轉軸頻率與皮帶激振之調變影響





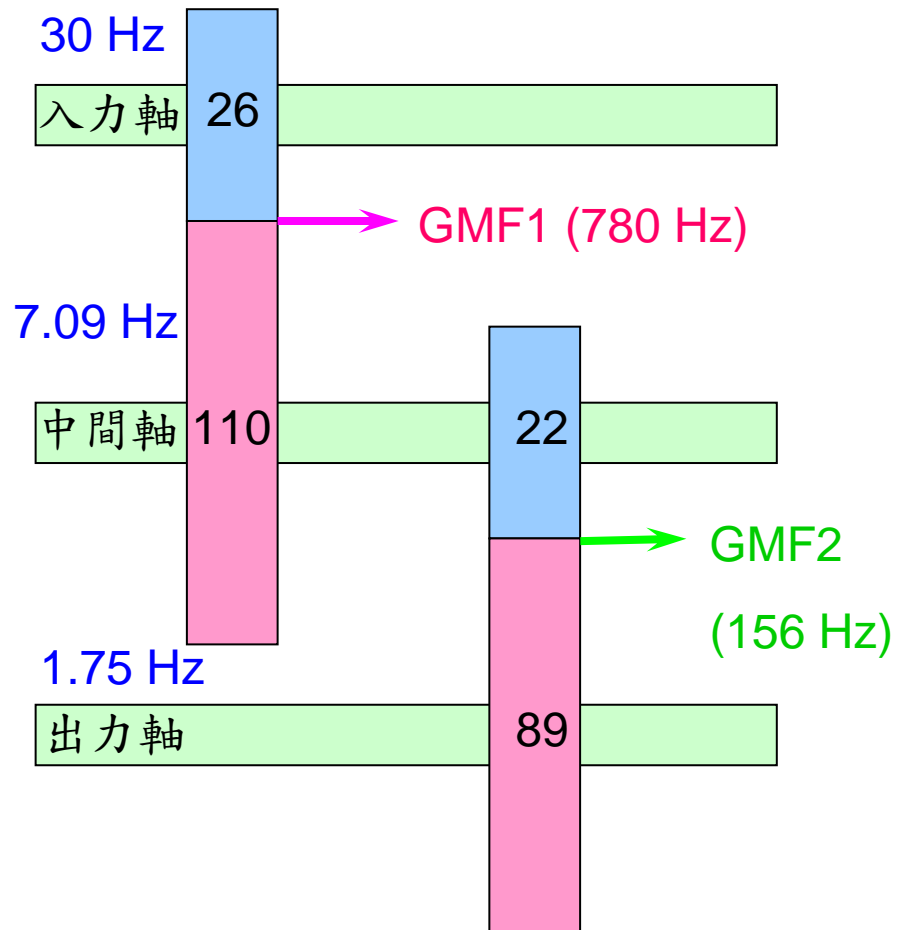
# 電梯減速齒輪箱異音檢測





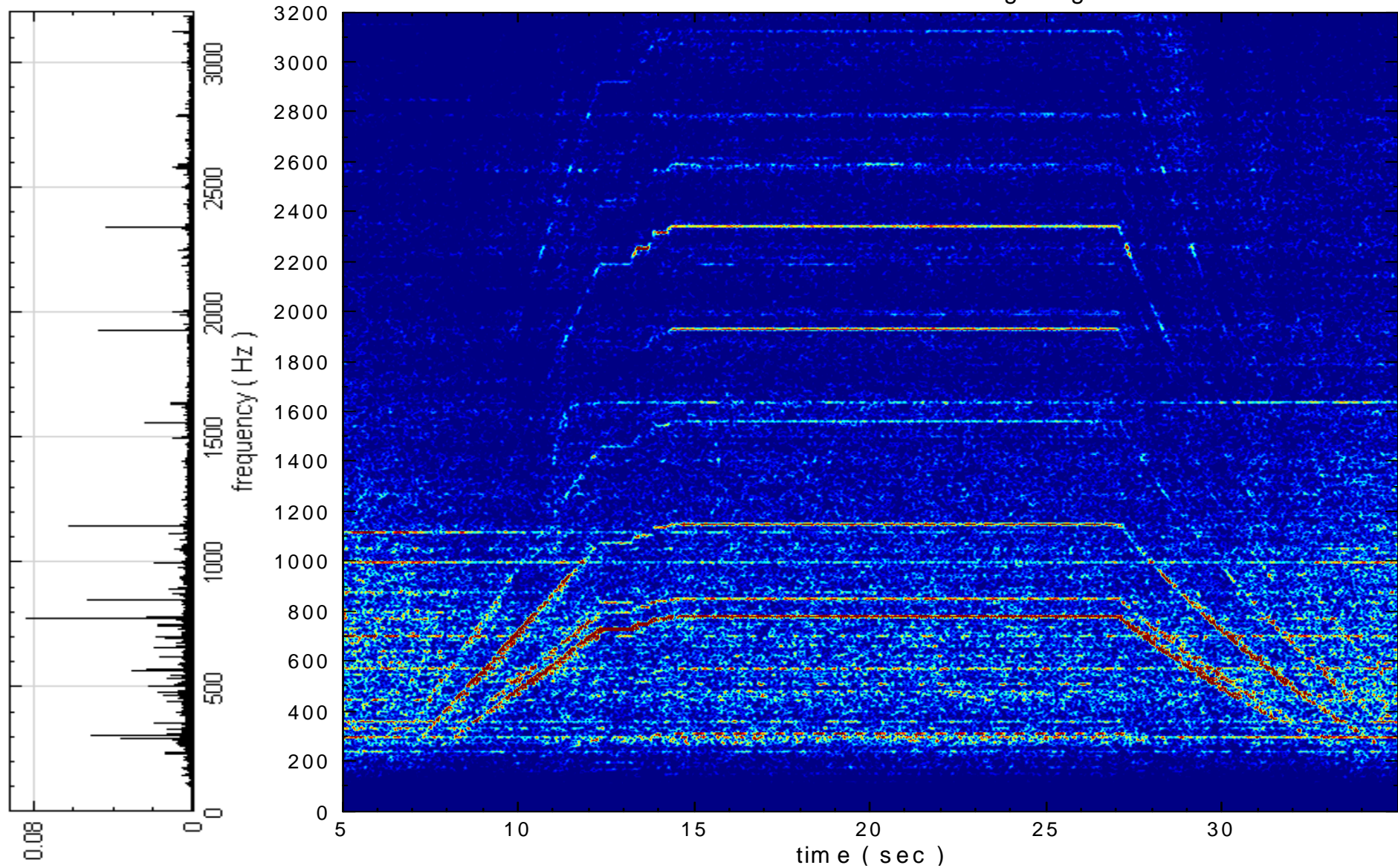
# 電源頻率60Hz-轉軸頻率及啮合頻率

轉軸頻率



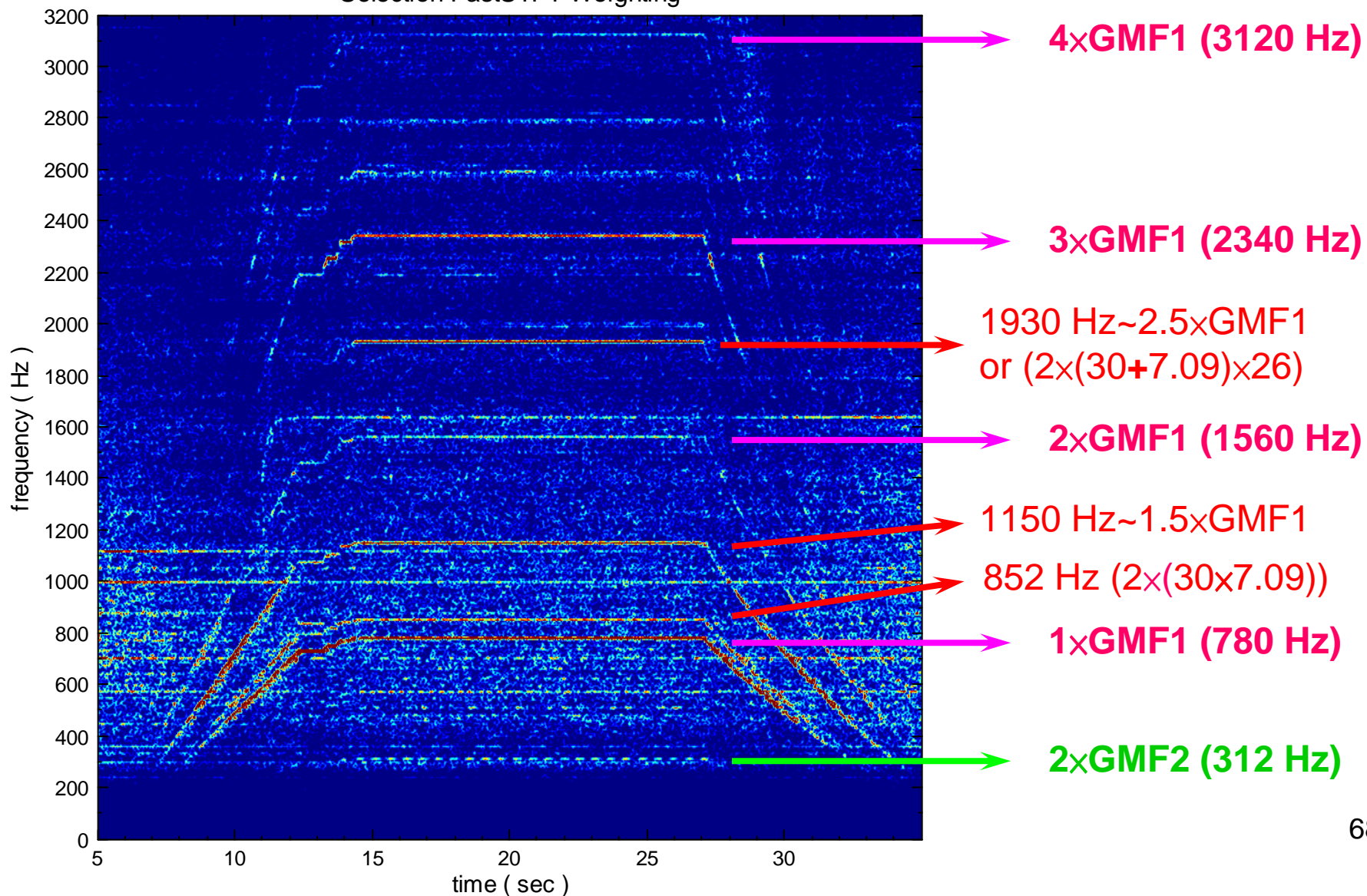
# 60Hz-正常生產運轉方向 聲音原始頻譜

Selection-FastSTFT-Weighting



# 60Hz-正常生產運轉方向 聲音A加權頻譜→人耳感受

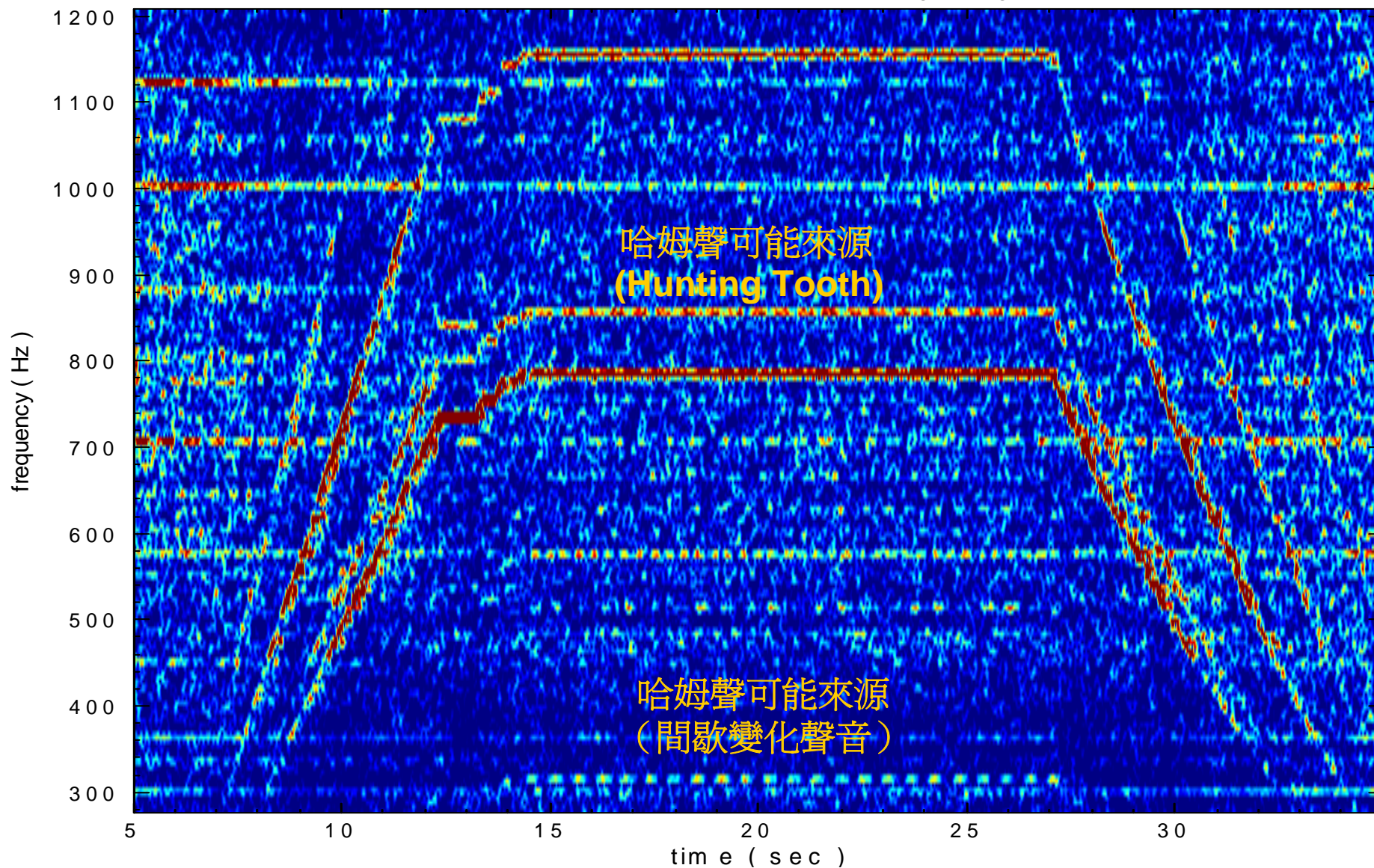
Selection-FastSTFT-Weighting





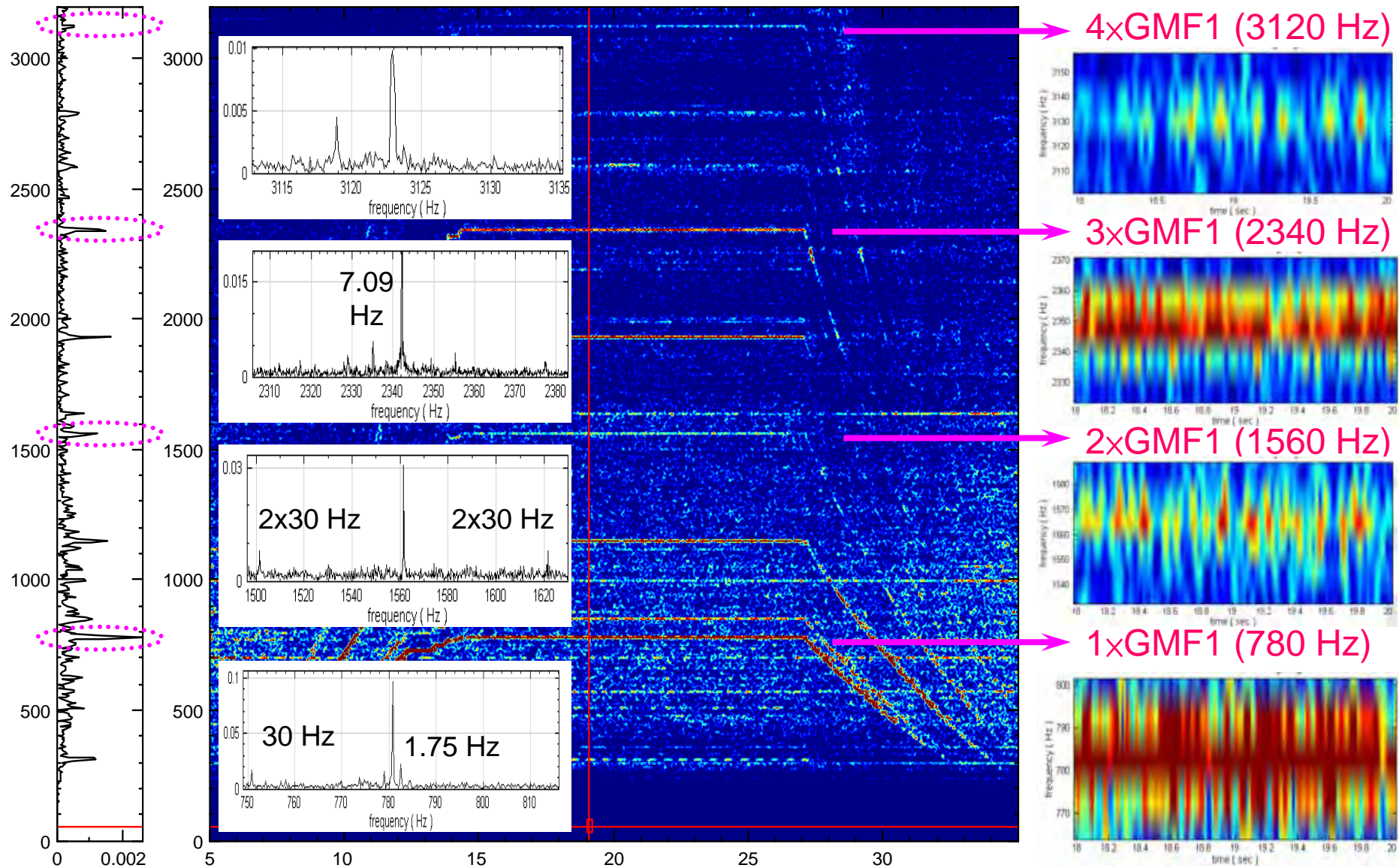
# 60Hz-正常生產運轉方向 聲音A加權頻譜→低頻區域

Selection-FastSTFT-Weighting

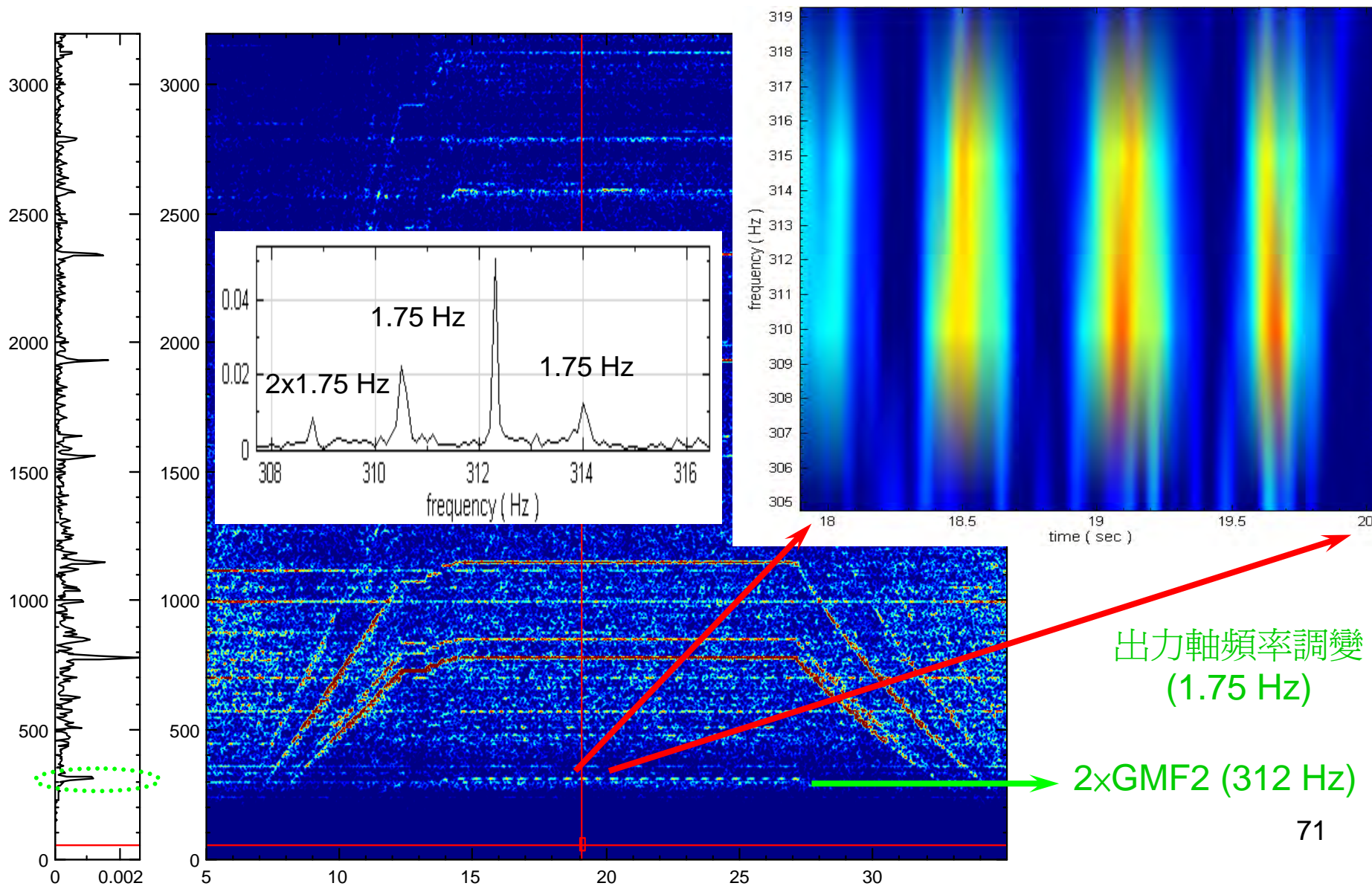




# 60Hz-正常生產運轉方向 入力軸與中間軸之嚙合頻率倍頻



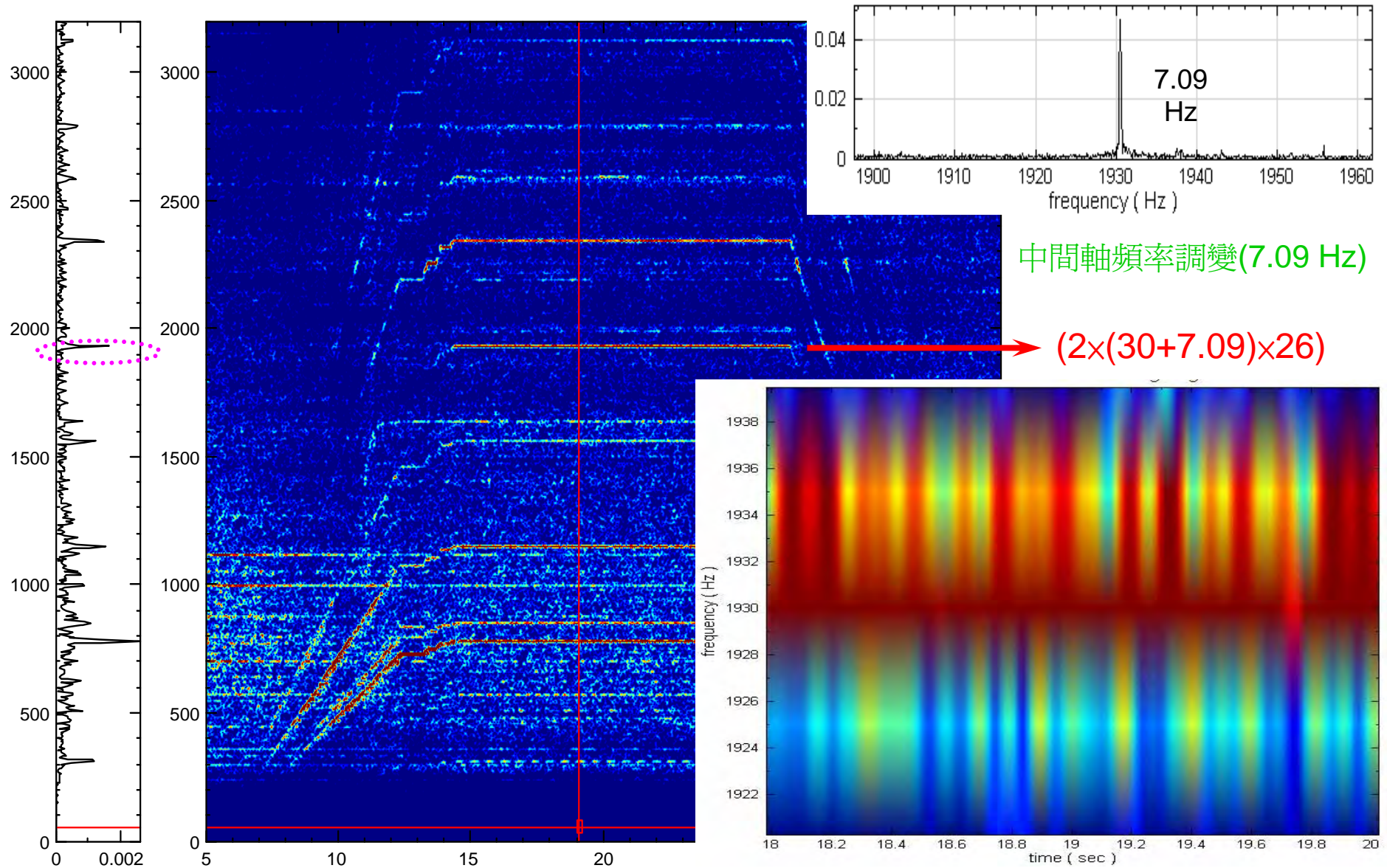
# 60Hz-正常生產運轉方向 中間軸與出力軸之嚙合頻率





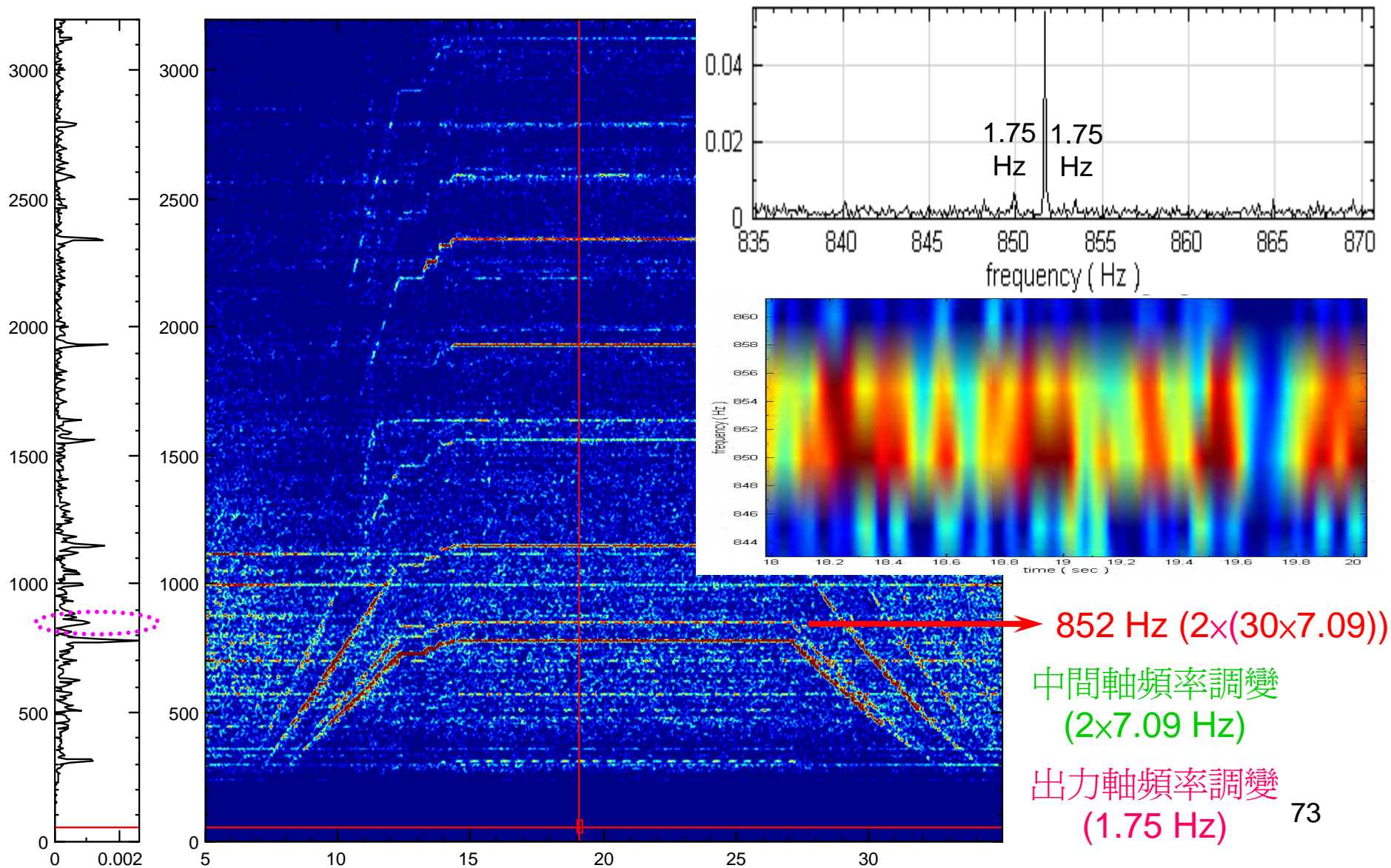
# 60Hz-正常生產運轉方向

## 其他問題頻率：Sum modulation 2倍頻



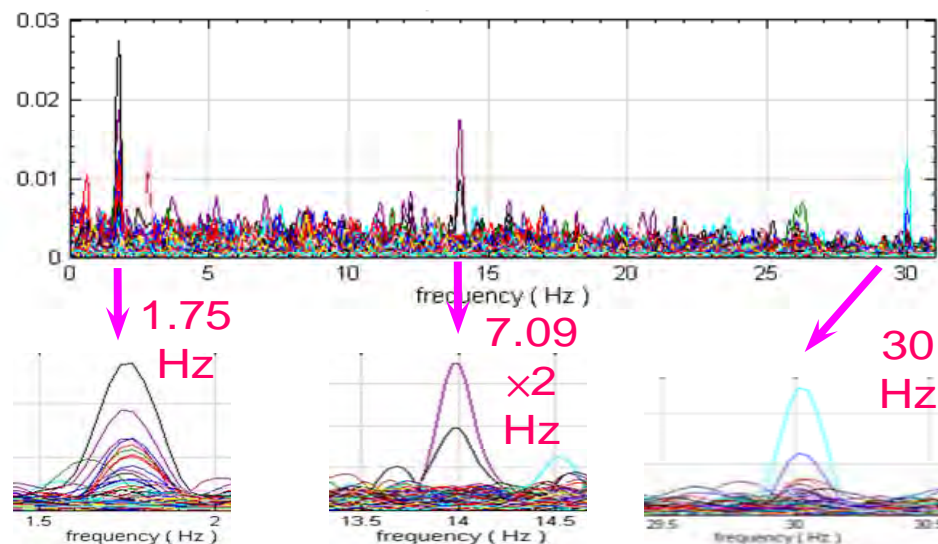
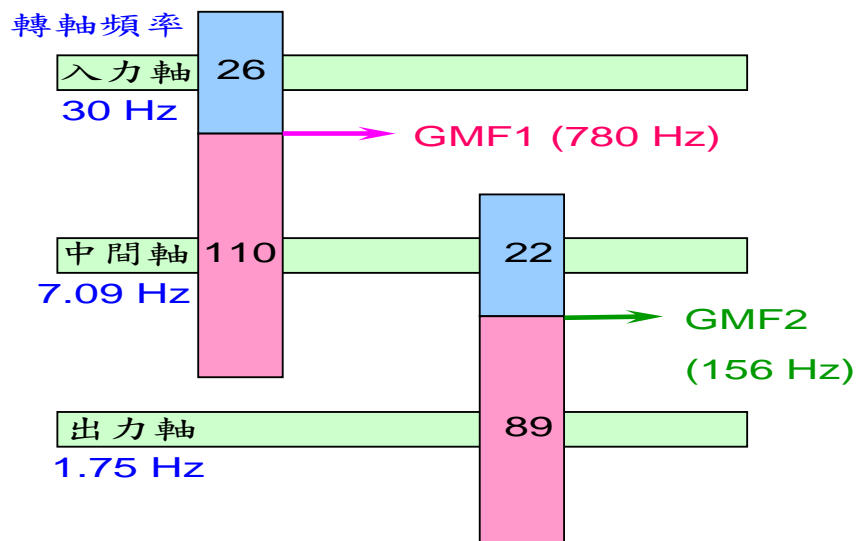
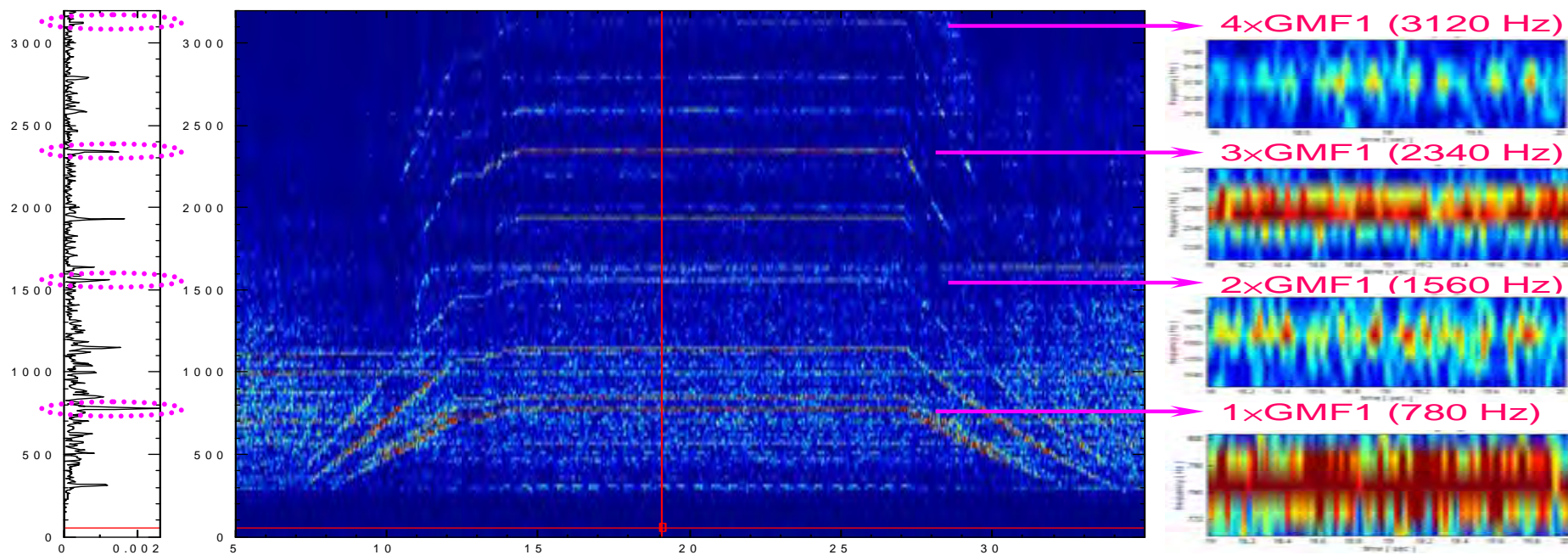
# 60Hz-正常生產運轉方向

## 其他問題頻率：Product modulation 2倍頻





# 嚙合頻率振幅不穩定之波動頻率分析







# HHT於軸承振動之健康診斷

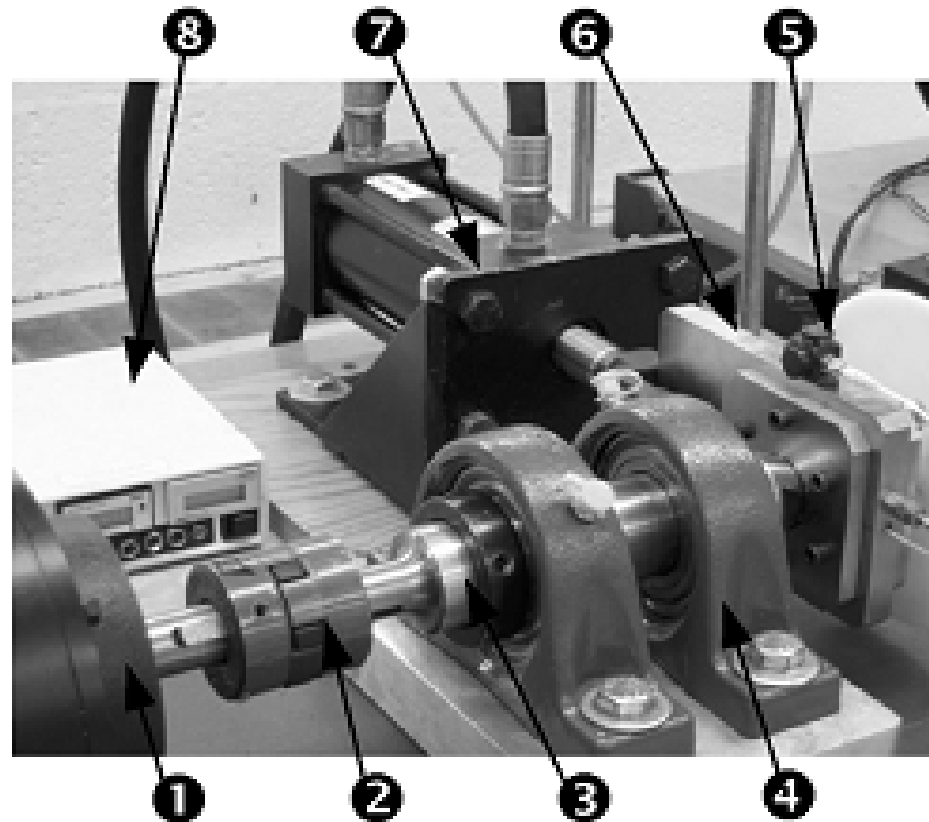
2320

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 55, NO. 6, DECEMBER 2006

## Hilbert–Huang Transform-Based Vibration Signal Analysis for Machine Health Monitoring

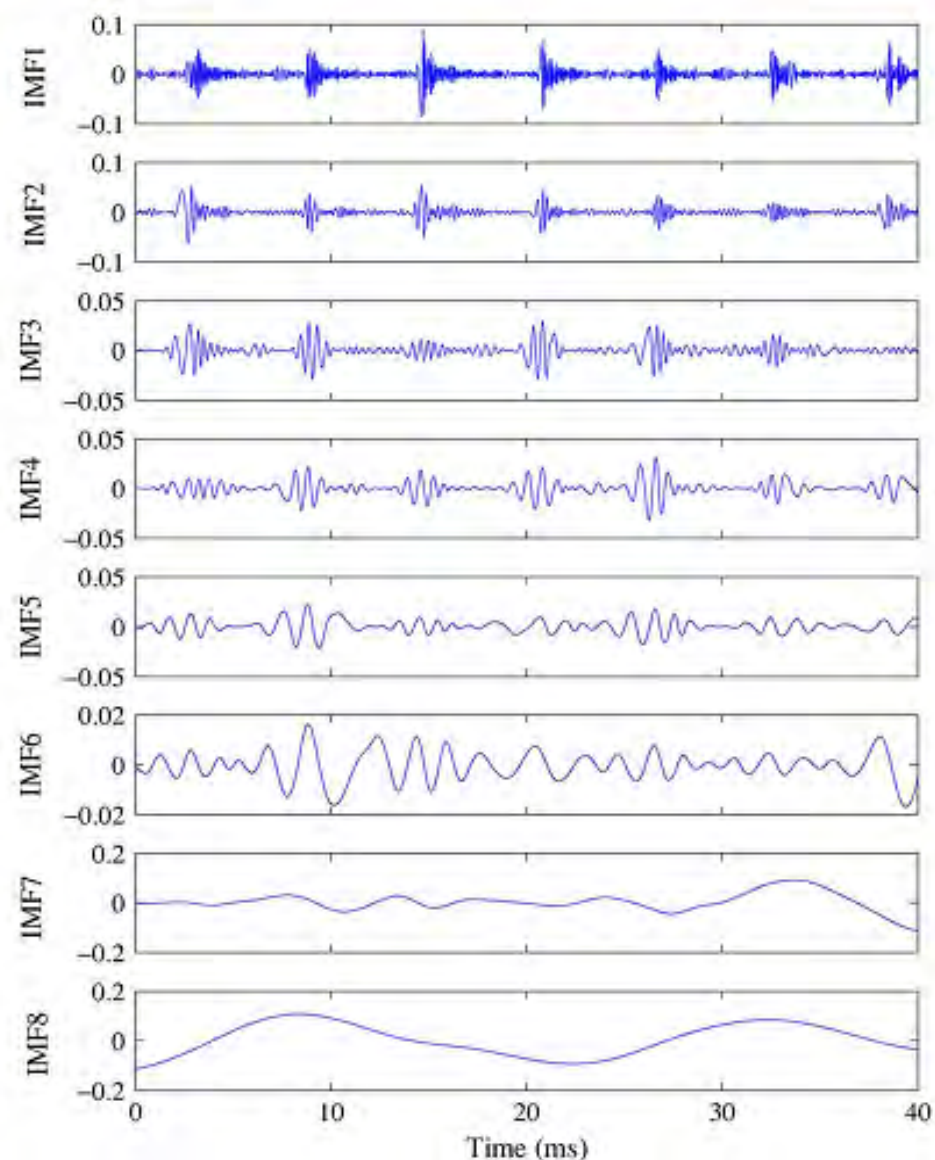
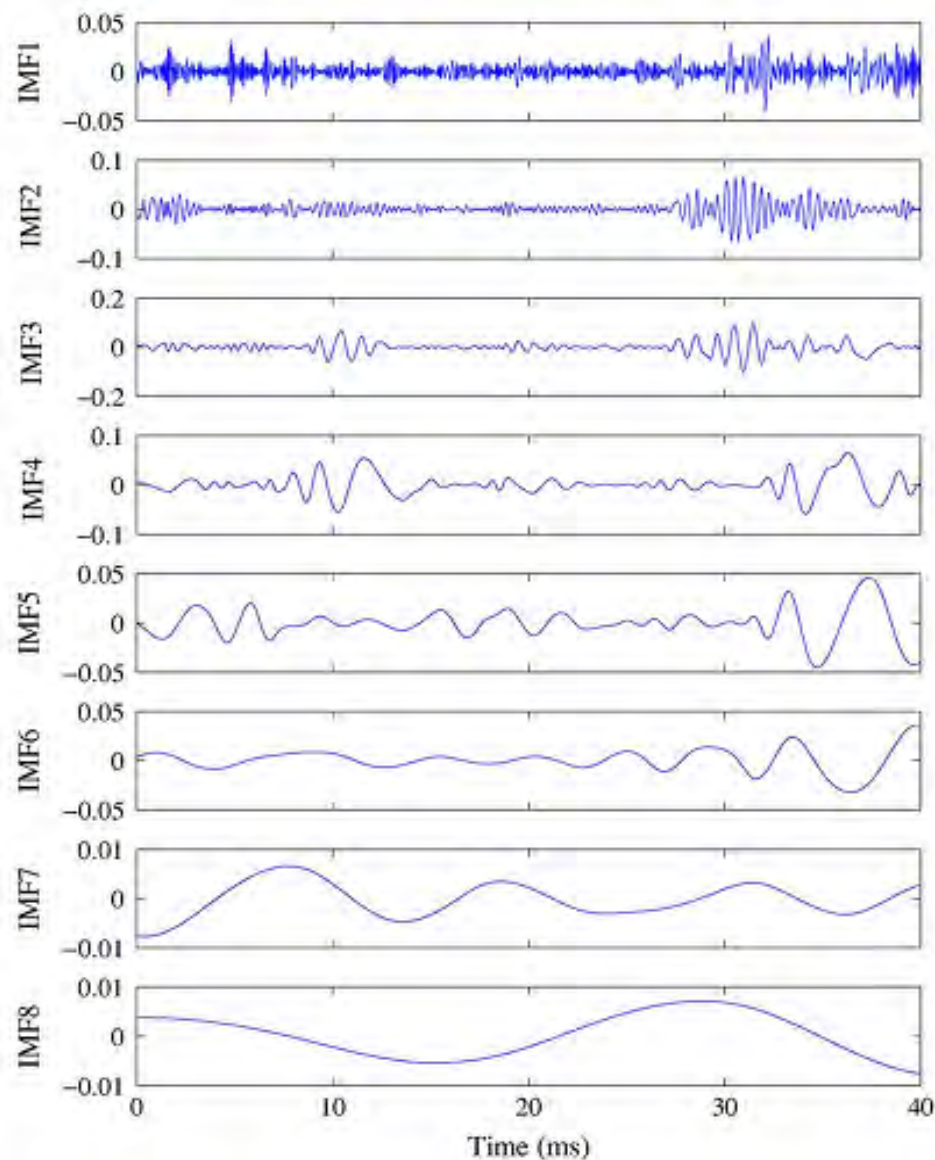
Ruqiang Yan, *Student Member, IEEE*, and Robert X. Gao, *Senior Member, IEEE*

# 實驗設置



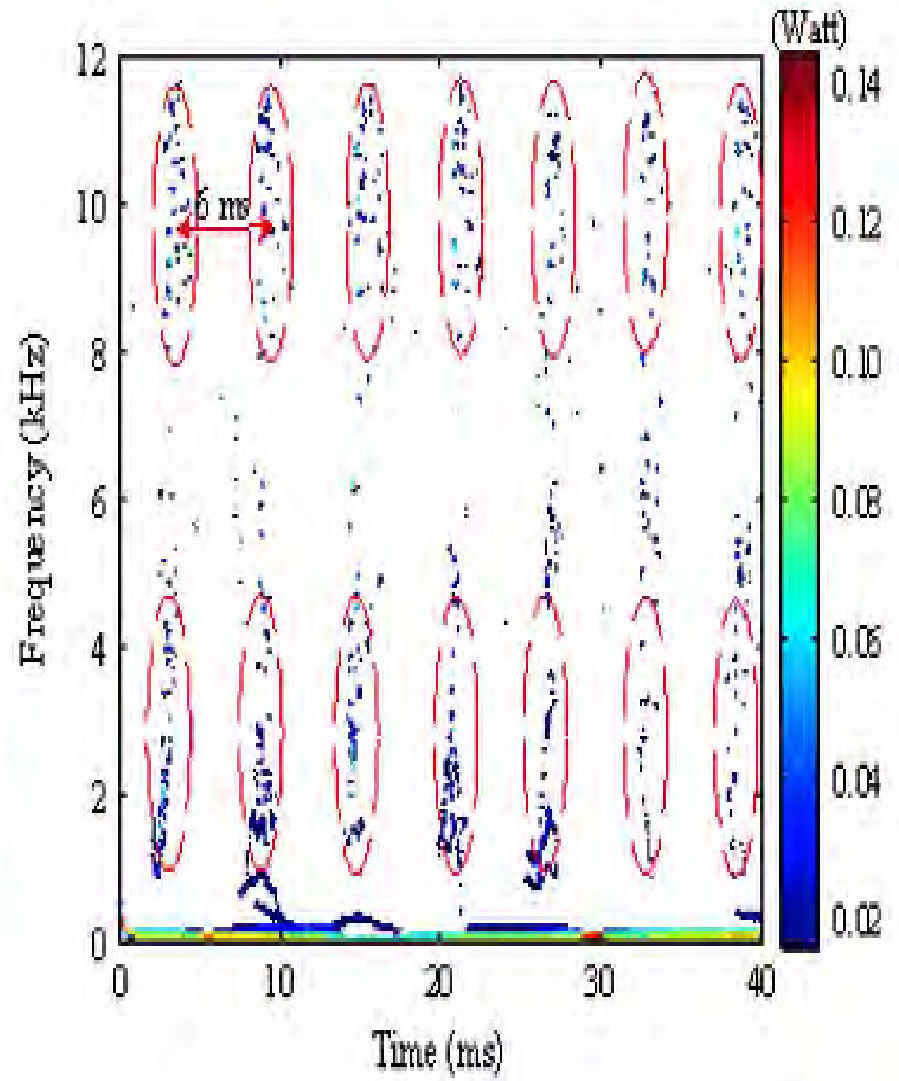
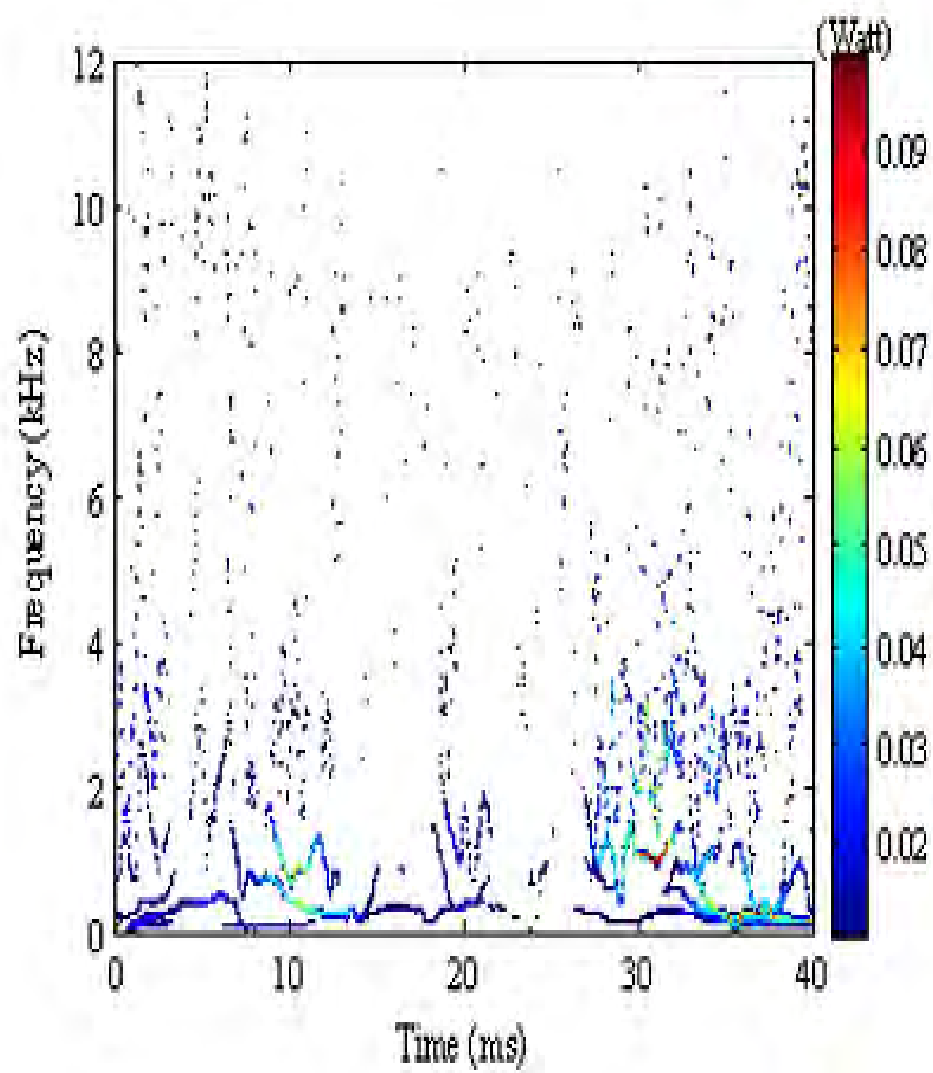
- |                       |                              |
|-----------------------|------------------------------|
| 1. DC Motor           | 2. Coupling                  |
| 3. Shaft              | 4. Pillow Blocks             |
| 5. Accelerometer      | 6. Test bearing with Housing |
| 7. Hydraulic Cylinder | 8. Speed Recorder            |

# EMD : 健康軸承vs.異常軸承

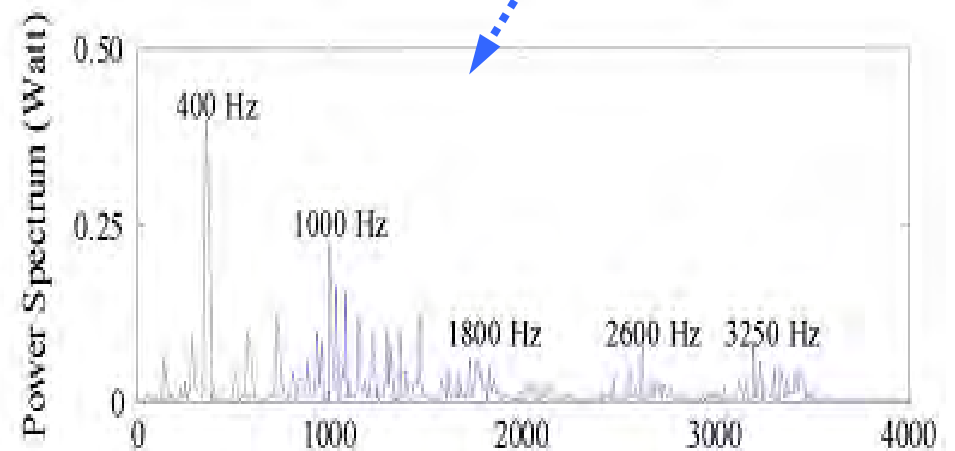
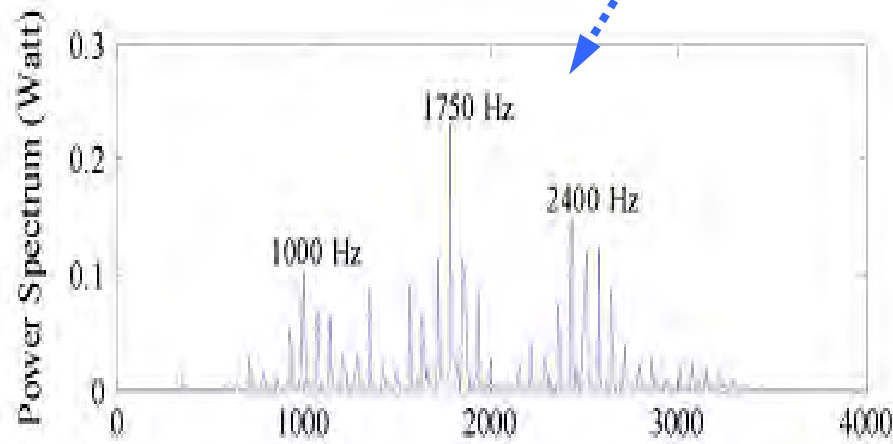
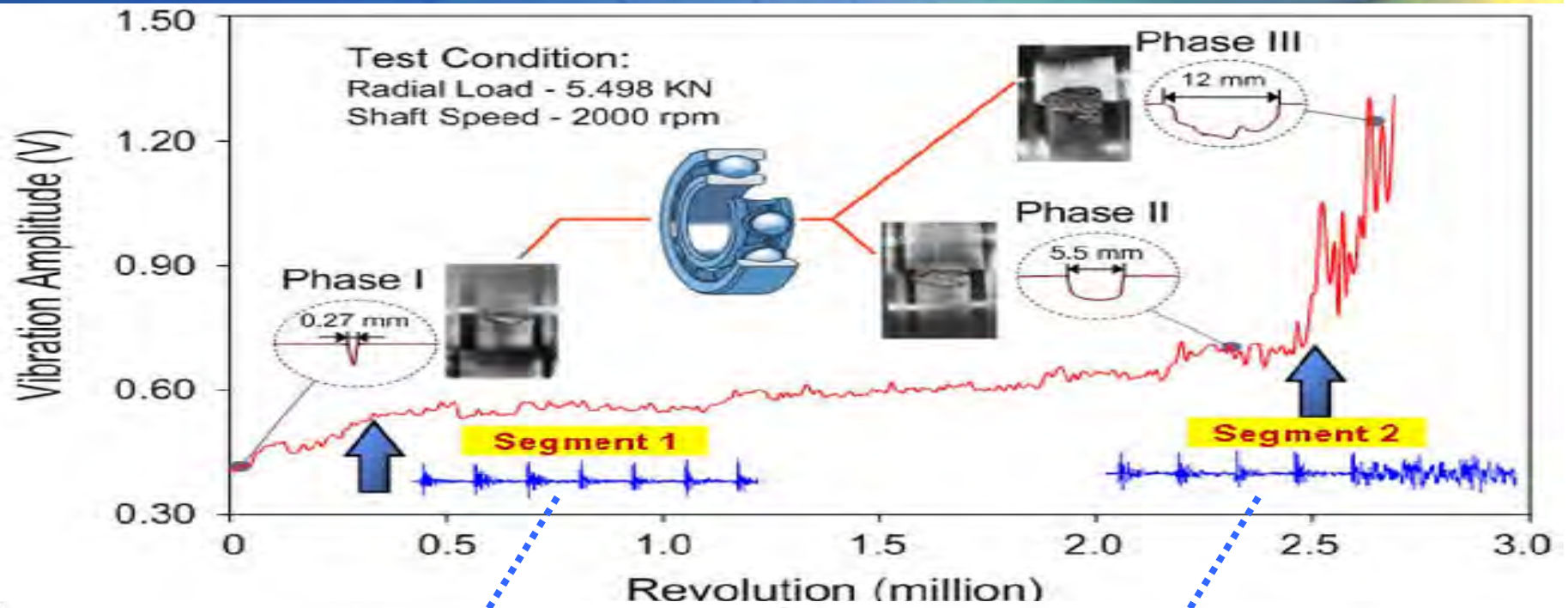




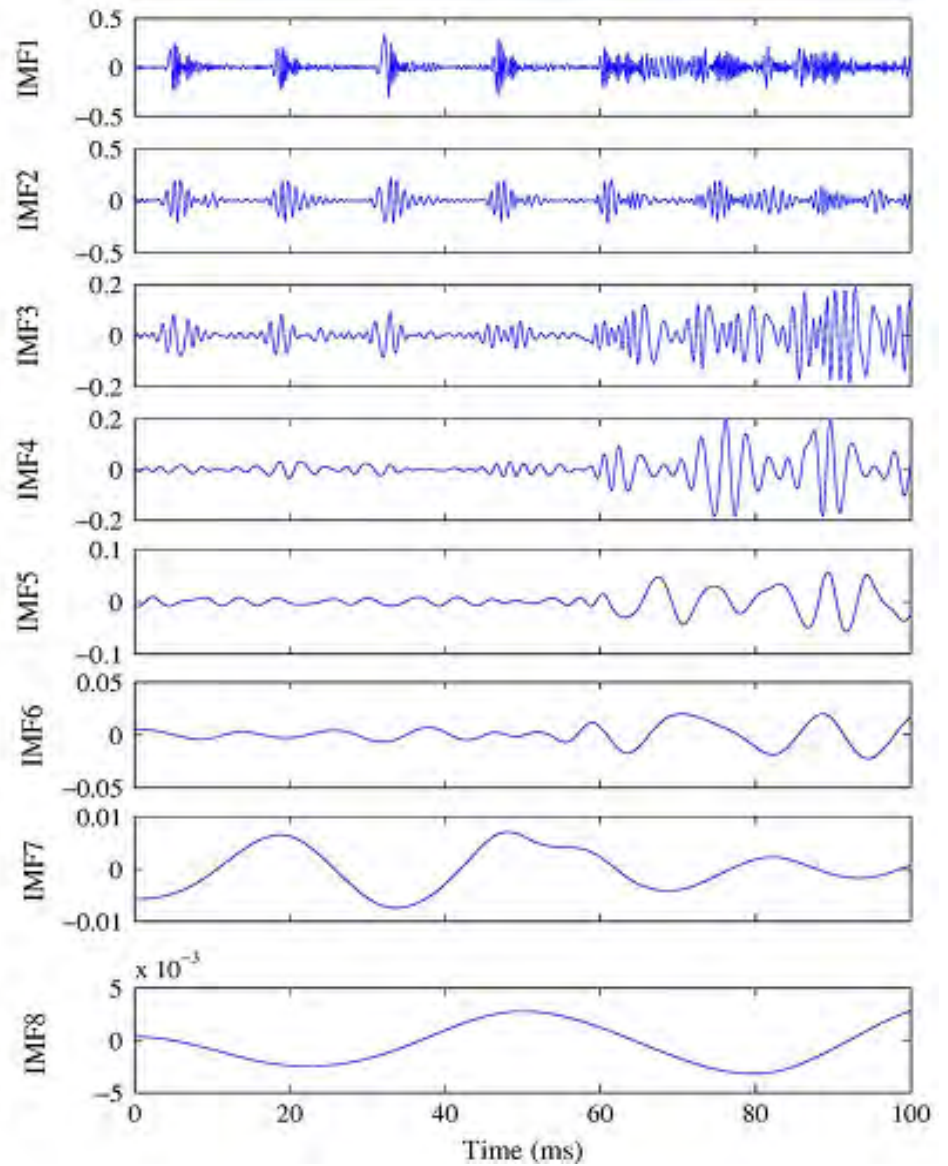
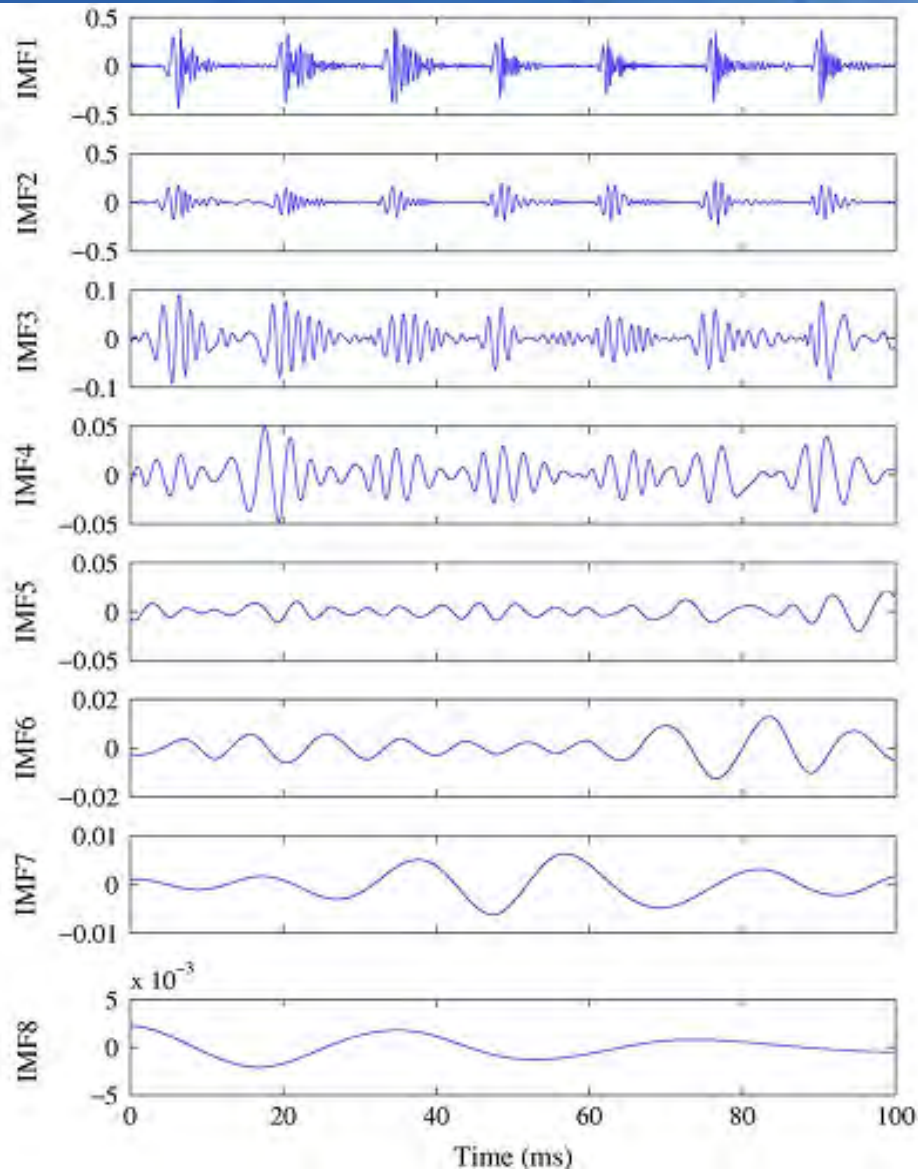
# HHT : 健康軸承 vs. 異常軸承



# 各損壞階段軸承之FFT比較

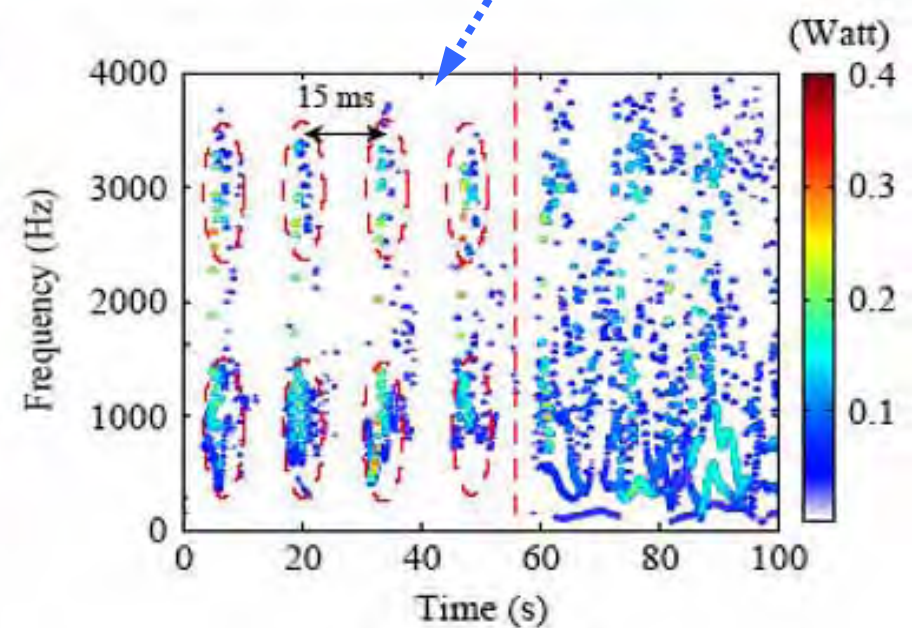
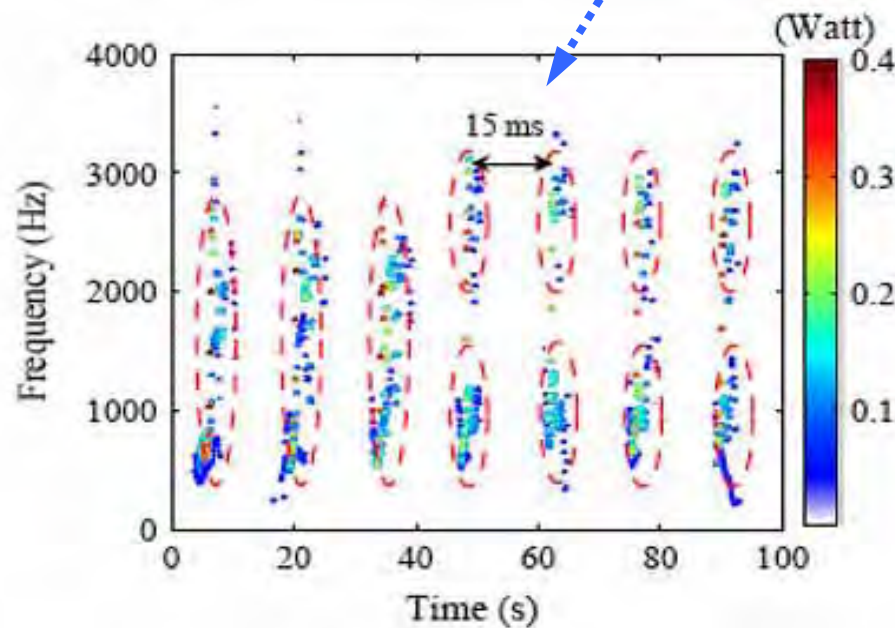
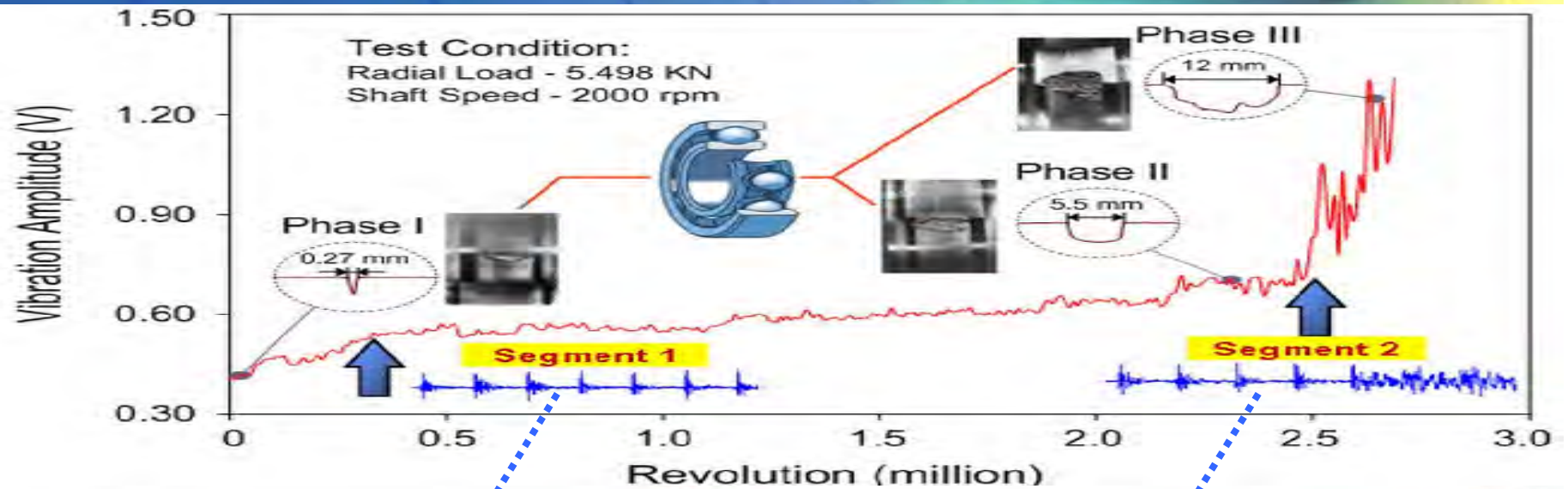


# EMD : Segment 1 vs. Segment 2





# 各損壞階段軸承之HHT比較





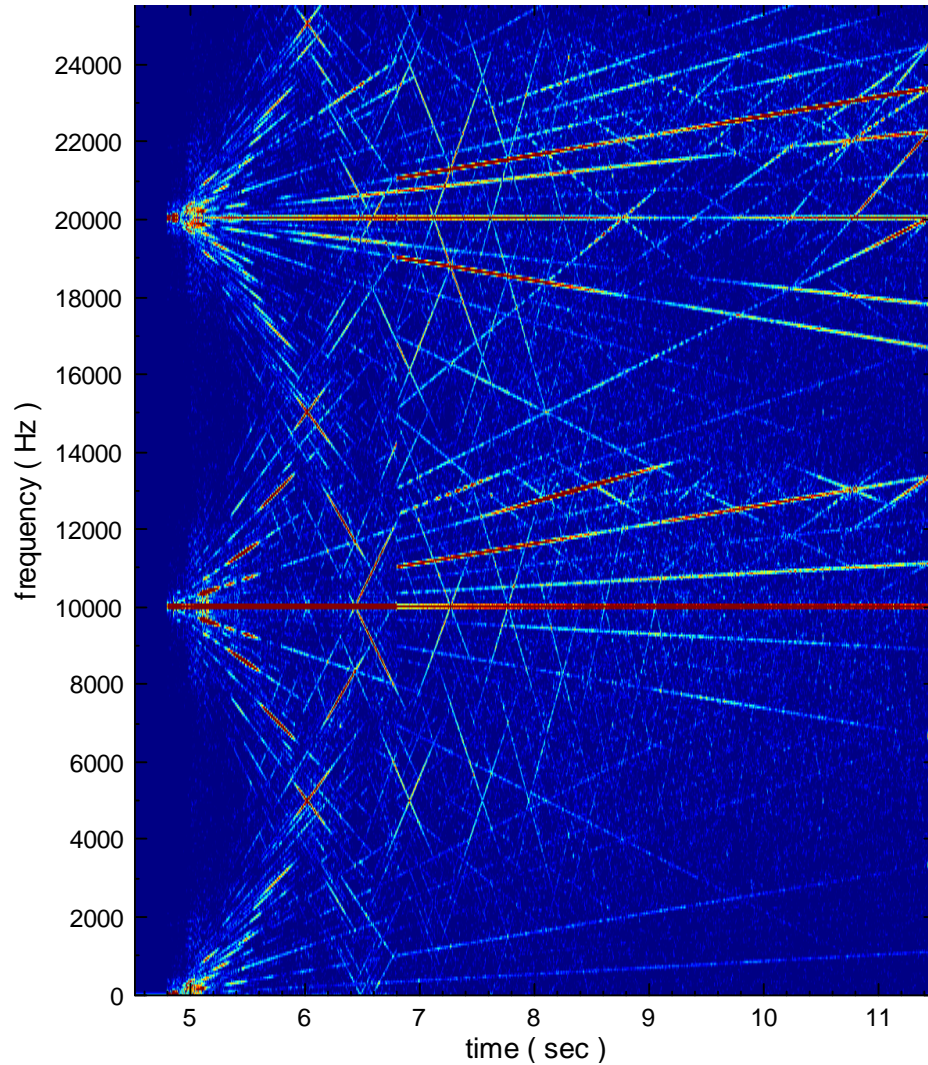
# Visual Signal應用



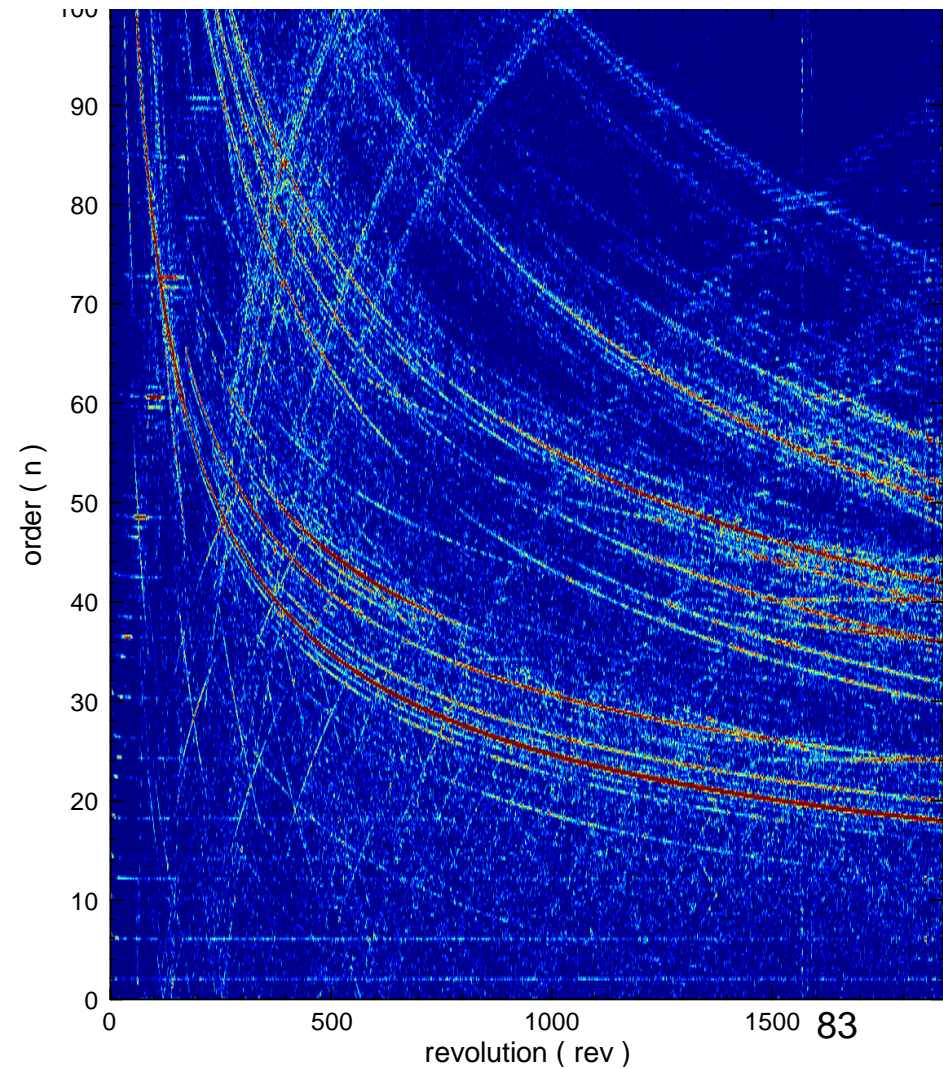
# 主軸之動態特性檢測

## 轉速倍頻、共振頻段、異常激振、頻率調變

變轉速時頻分析



轉速階次分析



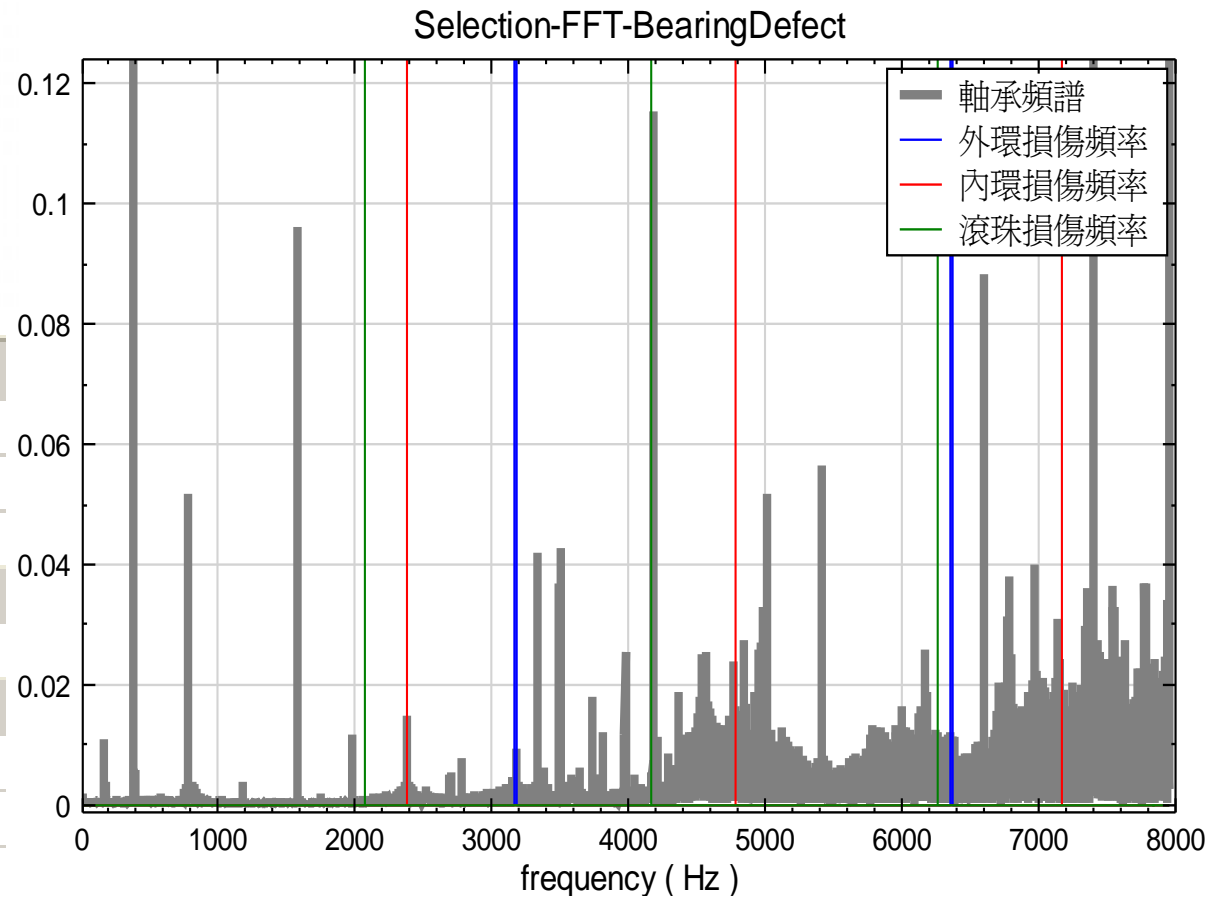


# 軸承之損壞特徵檢測

依據軸承規格自動計算內外環或滾珠損壞特徵頻率



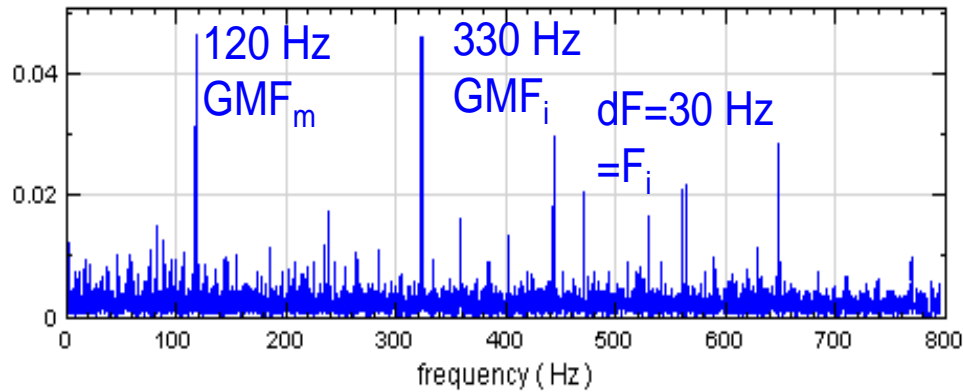
特徵頻率	
內環損傷頻率	2392.9923728949975
外環損傷頻率	3184.6076271050019
滾珠損傷頻率	2089.5379498952088
參數	
轉速	398.4
軸承規格	
軸承平均直徑	42.5
接觸角	15
滾珠直徑	7.94
滾珠數量	14



# 變速齒輪箱之嚙合異常檢測

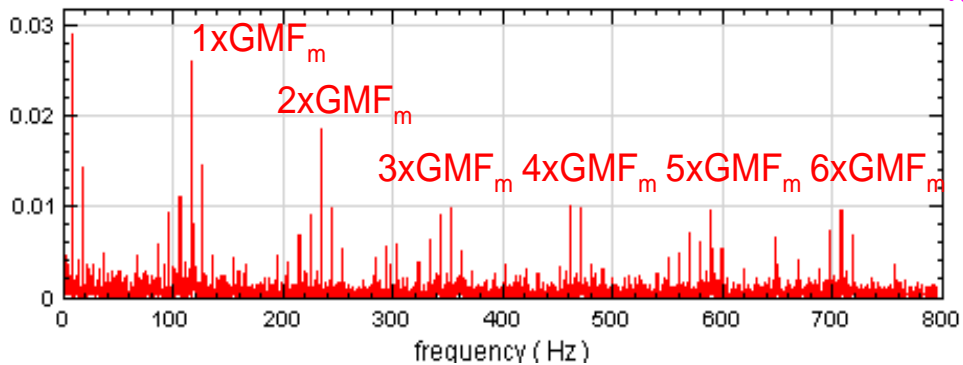
## 偏心、對心、鬆脫、背隙、磨損、斷齒

正常齒輪箱之包絡線頻譜



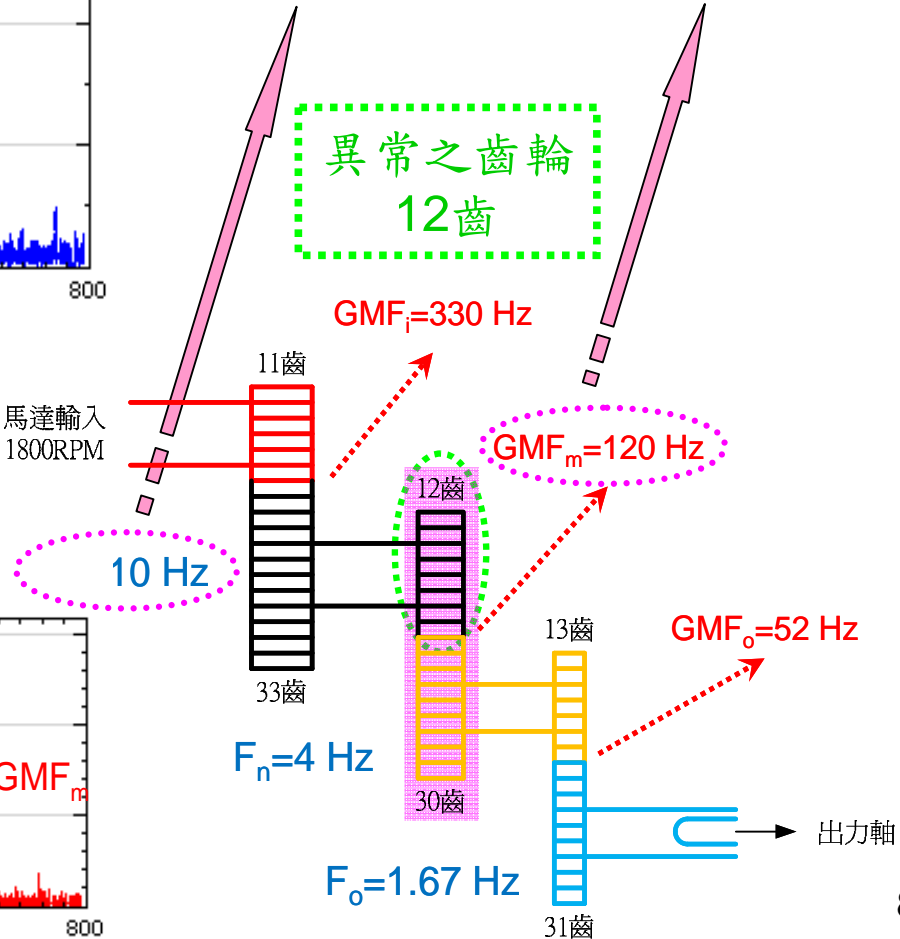
$F_i=30 \text{ Hz}$  馬達輸入 1800RPM

異常齒輪箱之包絡線頻譜



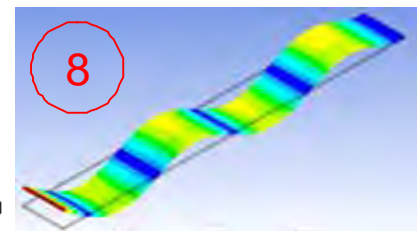
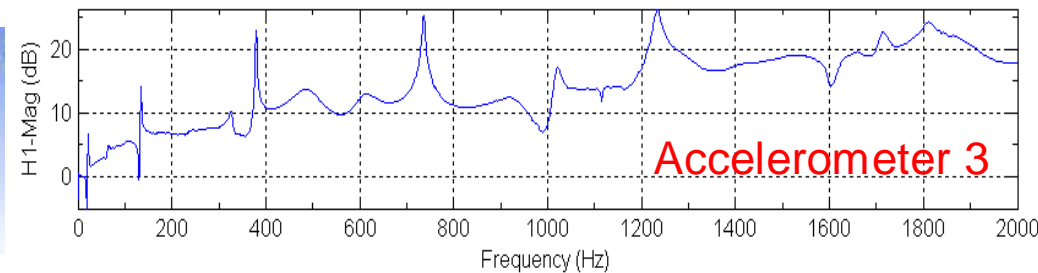
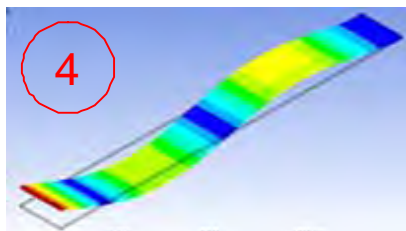
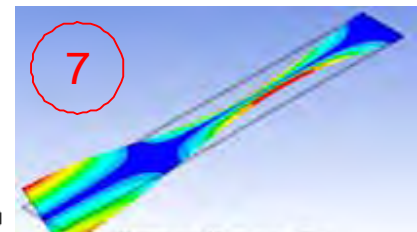
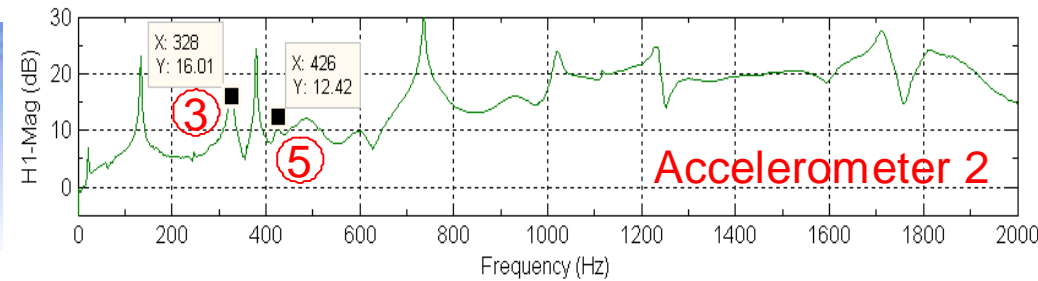
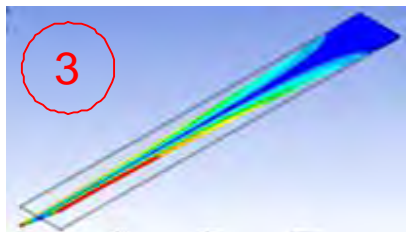
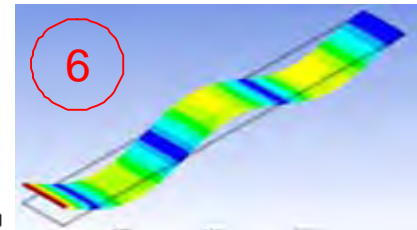
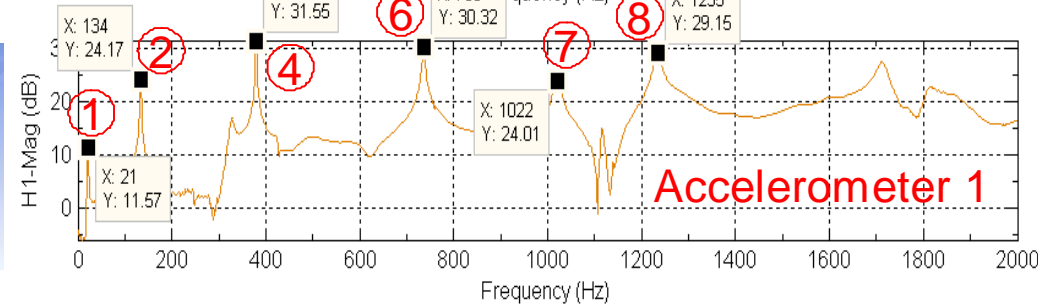
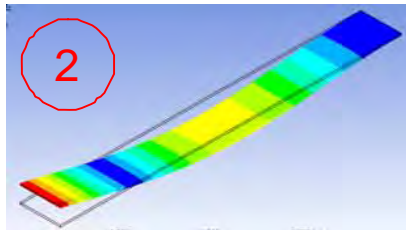
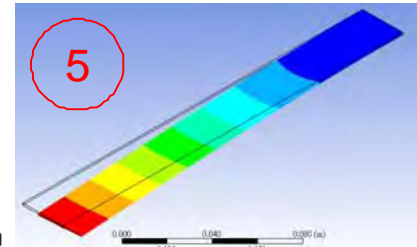
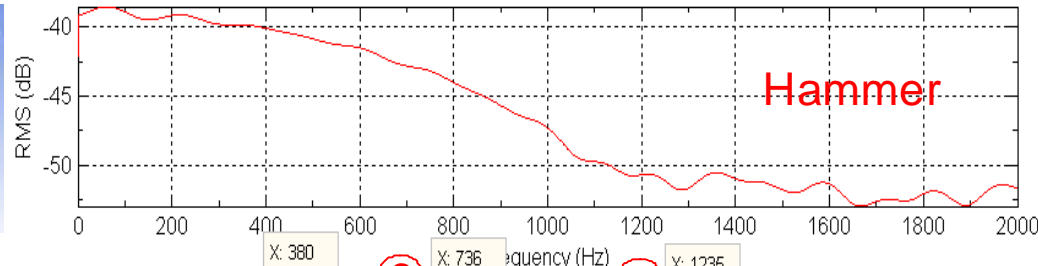
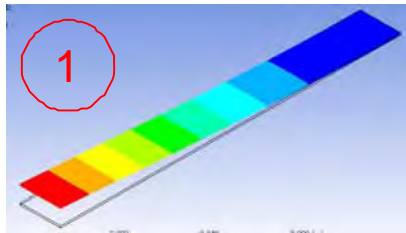
異常之  
轉速調變頻率

異常之  
嚙合頻率



# 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



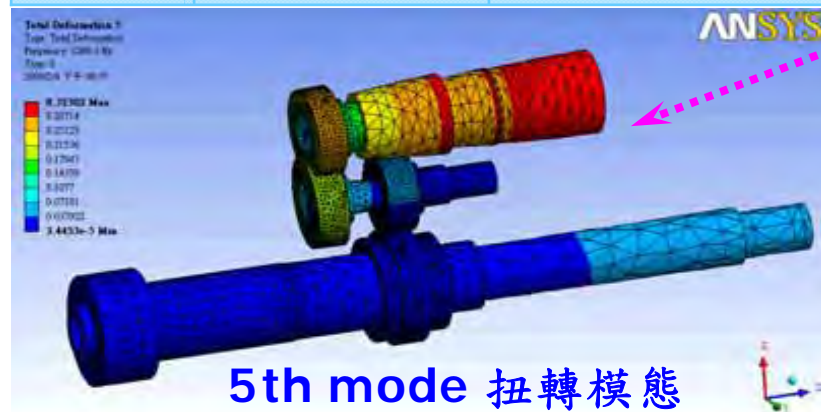


# 結構之自然頻率檢測

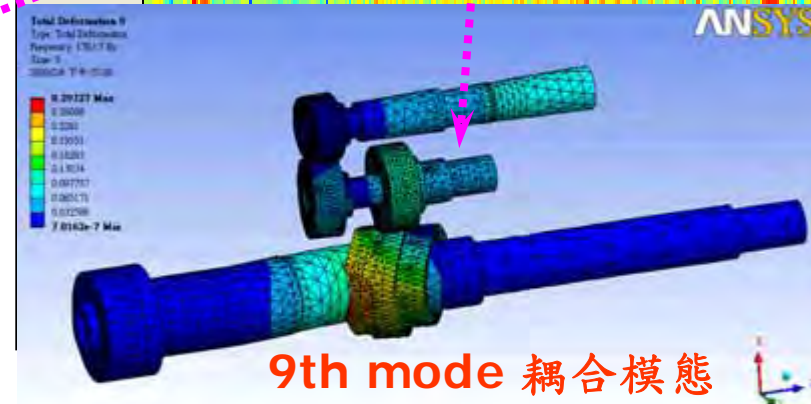
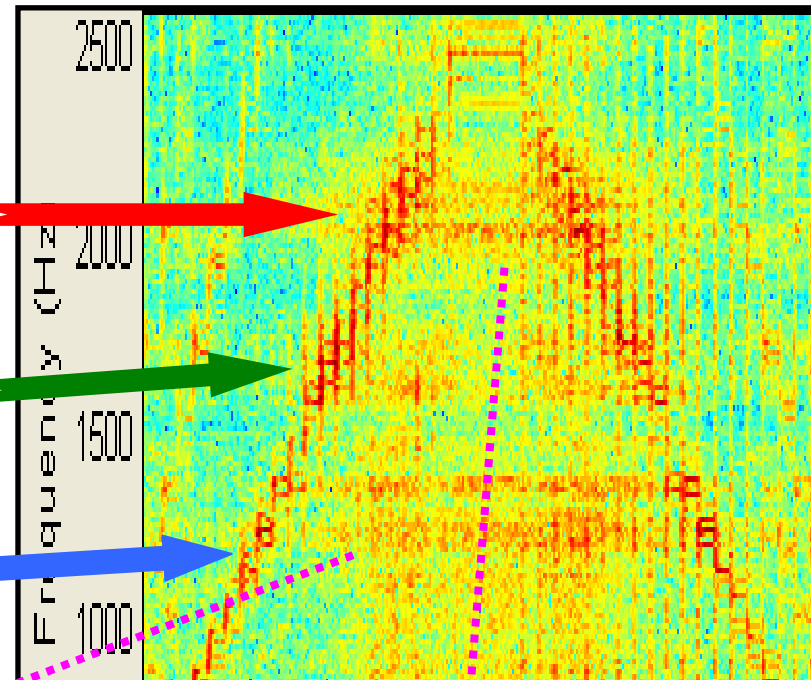
## 利用變轉速時頻驗證有限元素分析之正確性

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



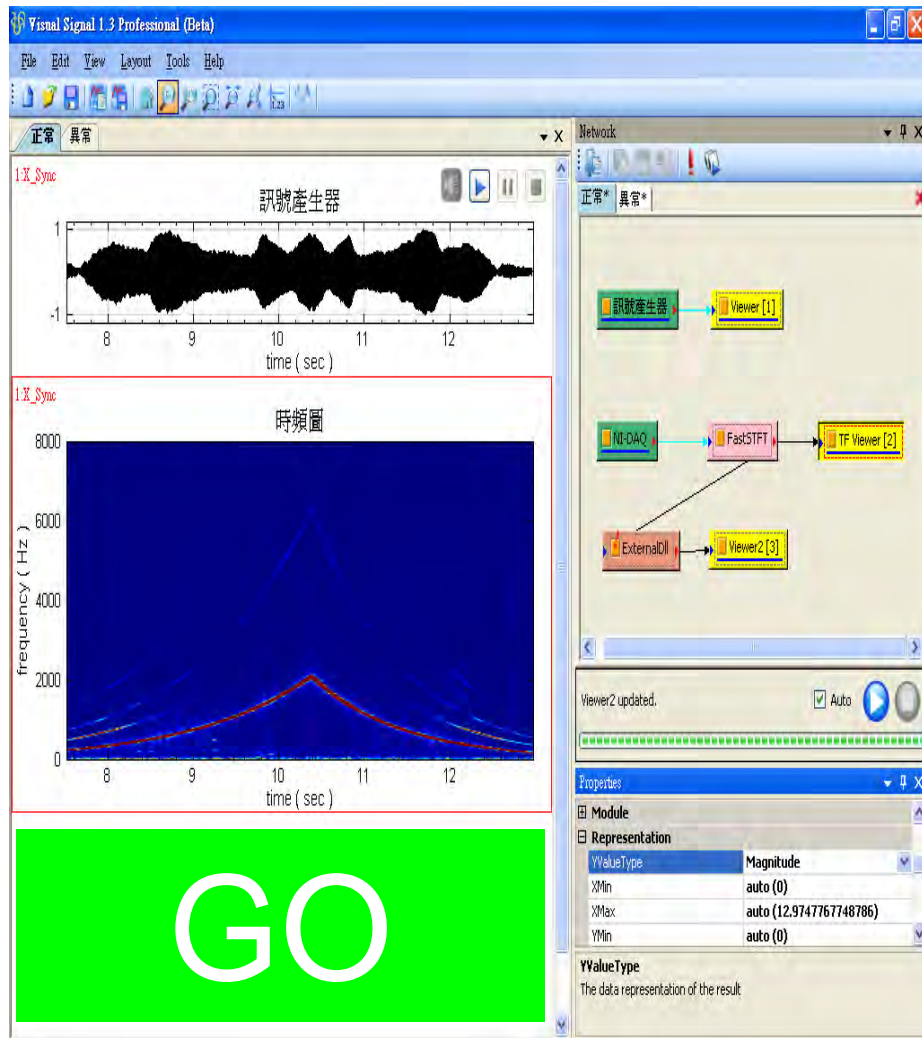
量測結果：



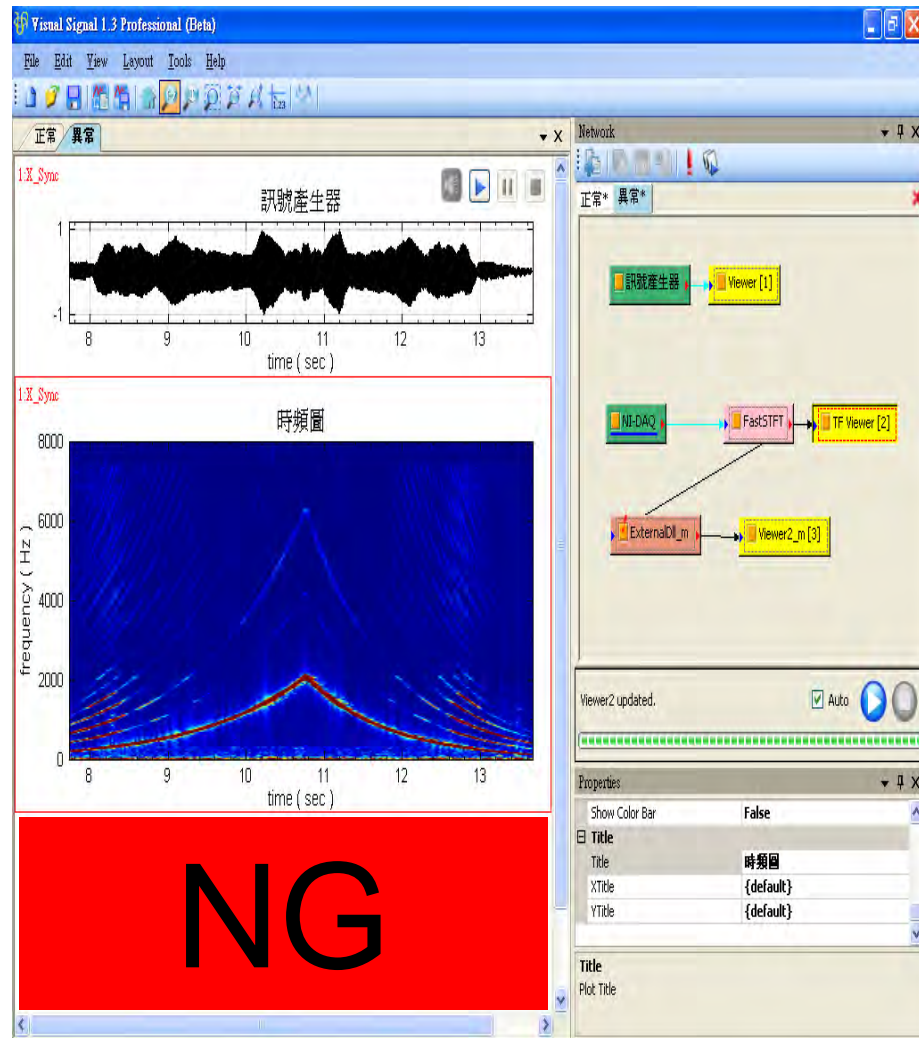
# 出廠之振噪品管檢測

## 客製化自動檢測流程、訊號產生器、客製化品管介面

出廠異音檢測：合格



出廠異音檢測：不合格



# Visual Signal 於各應用層面可檢測項目

