利用時頻與多尺度熵分析螺桿之螺帽預壓失效的研究

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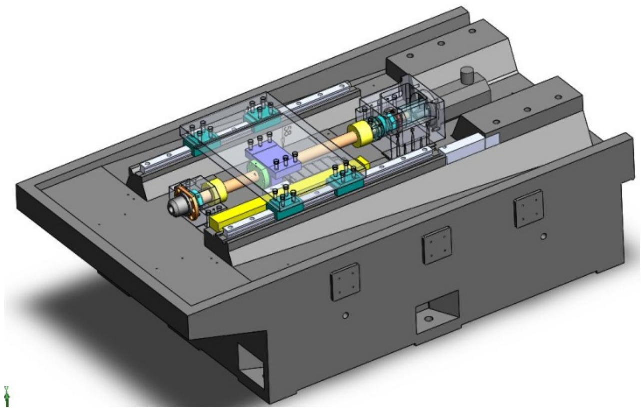
智能化螺桿計畫的分工架構

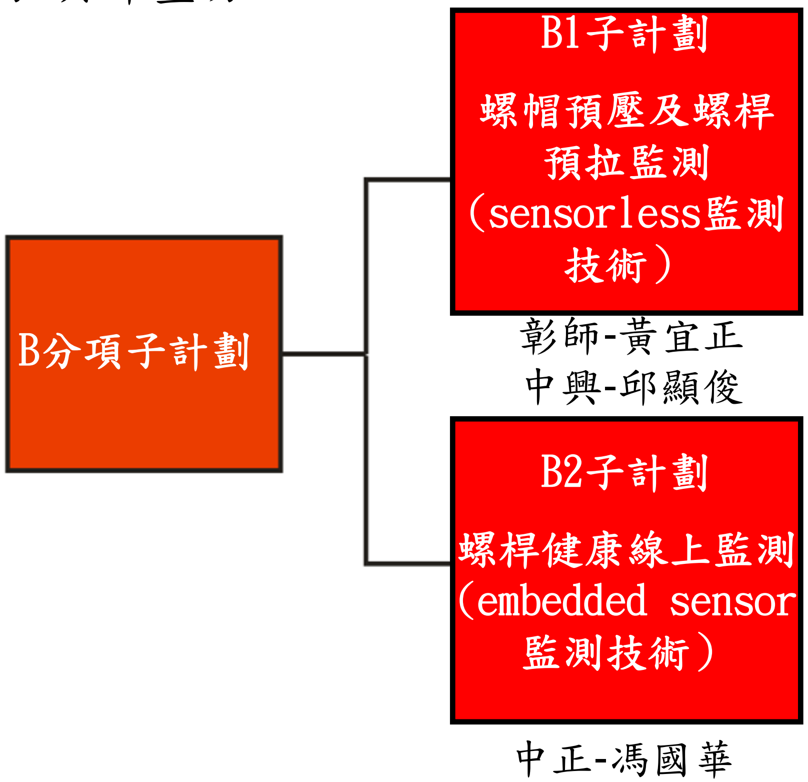
分項計畫目標：

◆ 透過精密機械發展中心、寶元數控與上銀公司共同合作，建立實驗平台

1. 開發不同螺帽預壓量的螺桿(上銀公司提供五組) ，建立監測到螺帽預壓與螺桿預拉失效之Sensorless監測技術。
2. 開發嵌入式感測器(溫度、加速度)的智能化螺桿技術

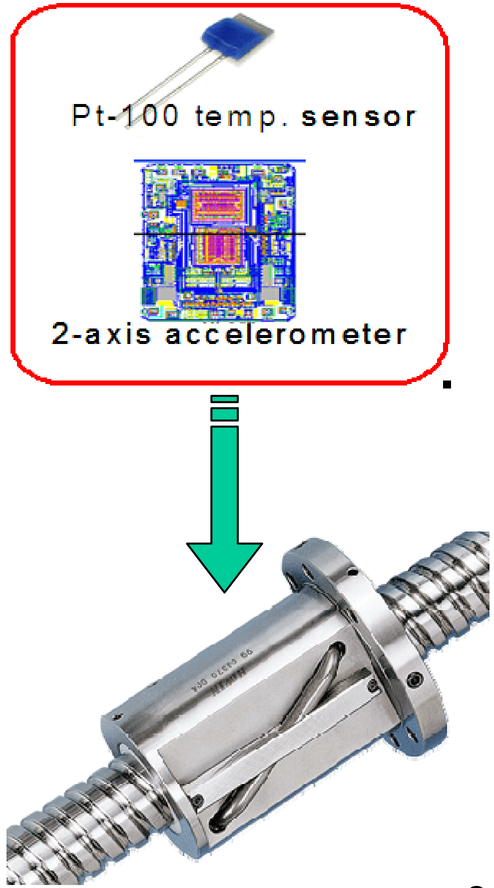


分項計畫分工：

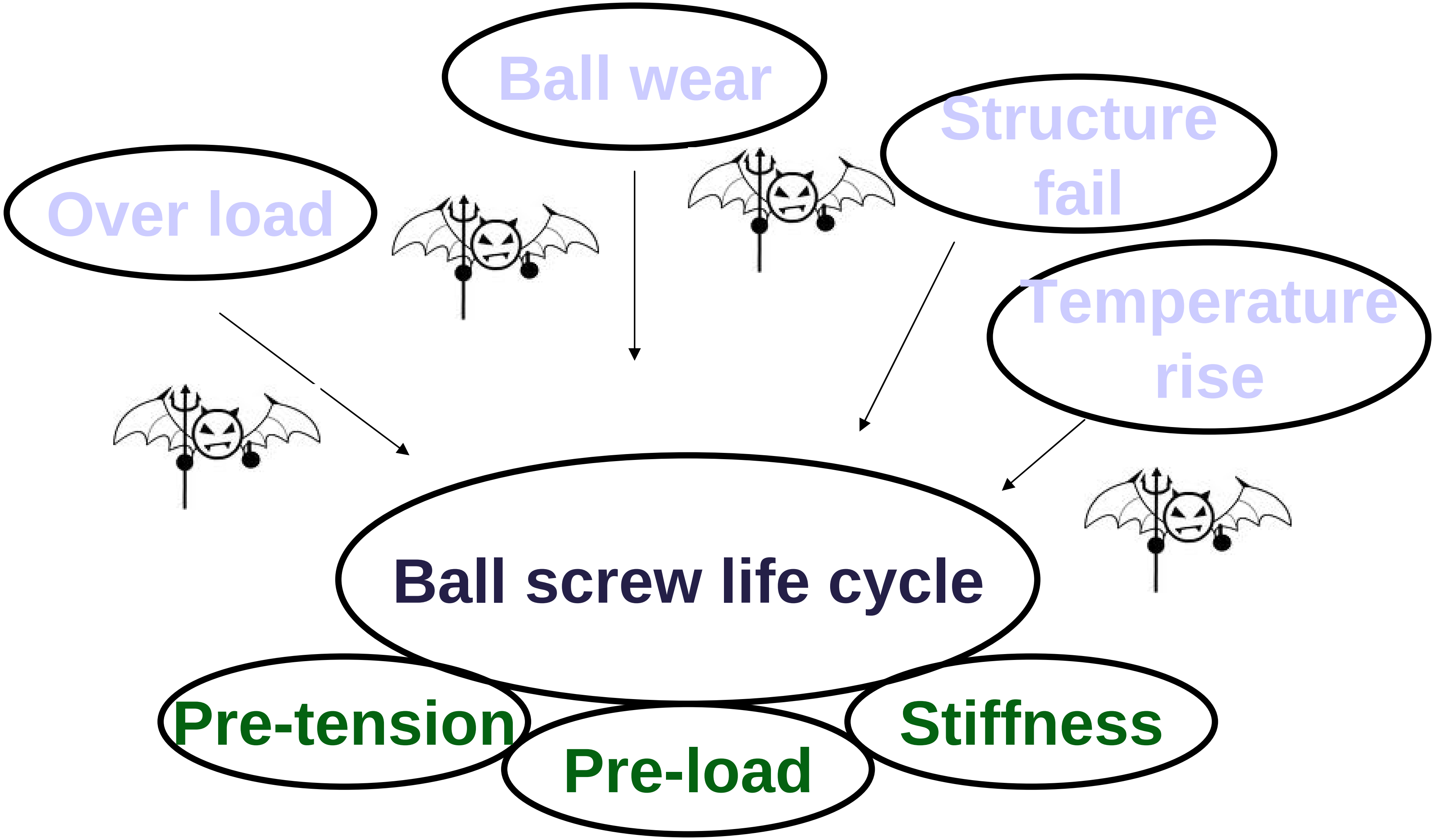


智能化螺桿之研究動機

- 螺桿由於長期使用，螺桿和螺帽間隙變大、滾珠過度磨耗，導致定位精確度變差，進而失效~使用者將難以選取穩定長時間的加工控制參數。
- 此外，螺桿上的切屑及油污可導致螺桿破損和滾珠的磨損增加，而縮短螺桿的壽命。
- 故可靠的螺桿健康監測乃極度重要，除可避免刀具使用者額外的成本支出；螺桿壽命的預測更可免去無預警的停工期。

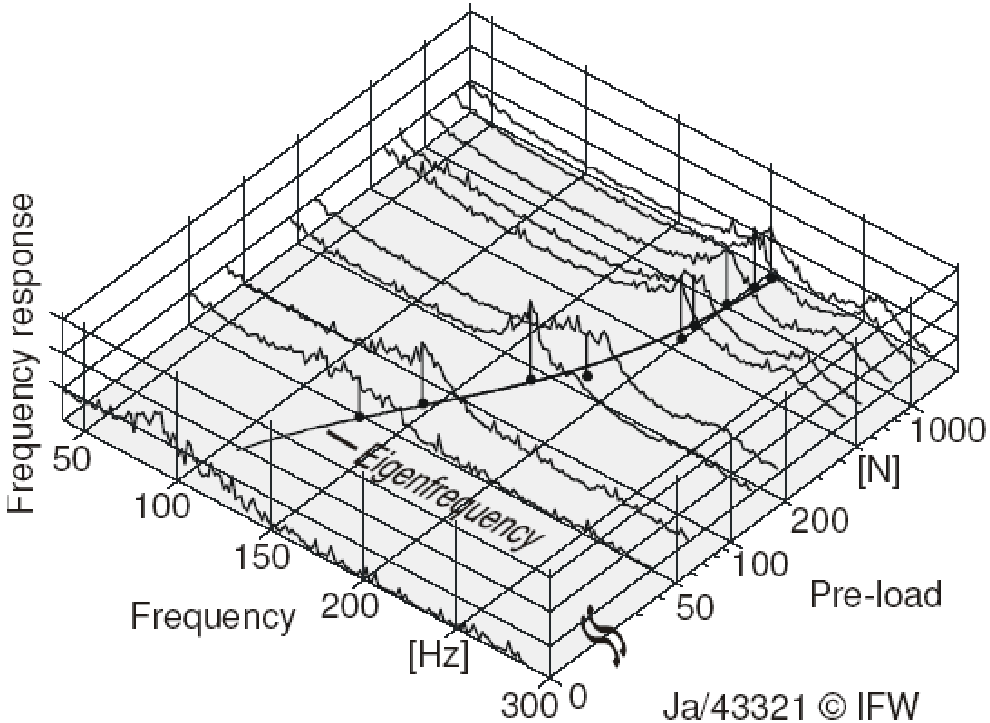


Research Motivation



滾珠螺桿壽命的預估 (I)

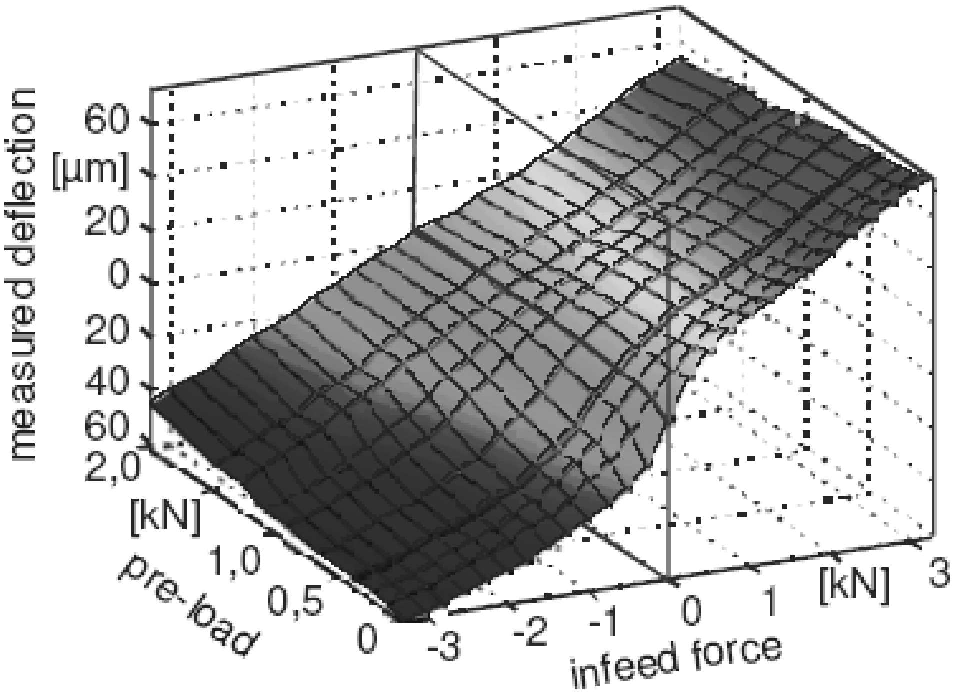
- 影響螺桿的自然頻率的因素，計有滑塊的質量、螺桿本身及螺帽的剛性等。
- 預壓的損失將導致螺桿系統特徵頻率(Eigen-frequency)降低。



Eigen-frequency 與預壓的關係

滾珠螺桿壽命的預估(II)

- 未磨耗的滾珠螺桿具近線性的彈簧常數特徵。
- 當滾珠磨損後，螺桿間隙變大，使得低進給力時螺桿系統有較低的剛性。因而線性的彈簧常數呈“S”形變化（如右圖）。



螺桿量測的進給力與變形量之關係

Outline

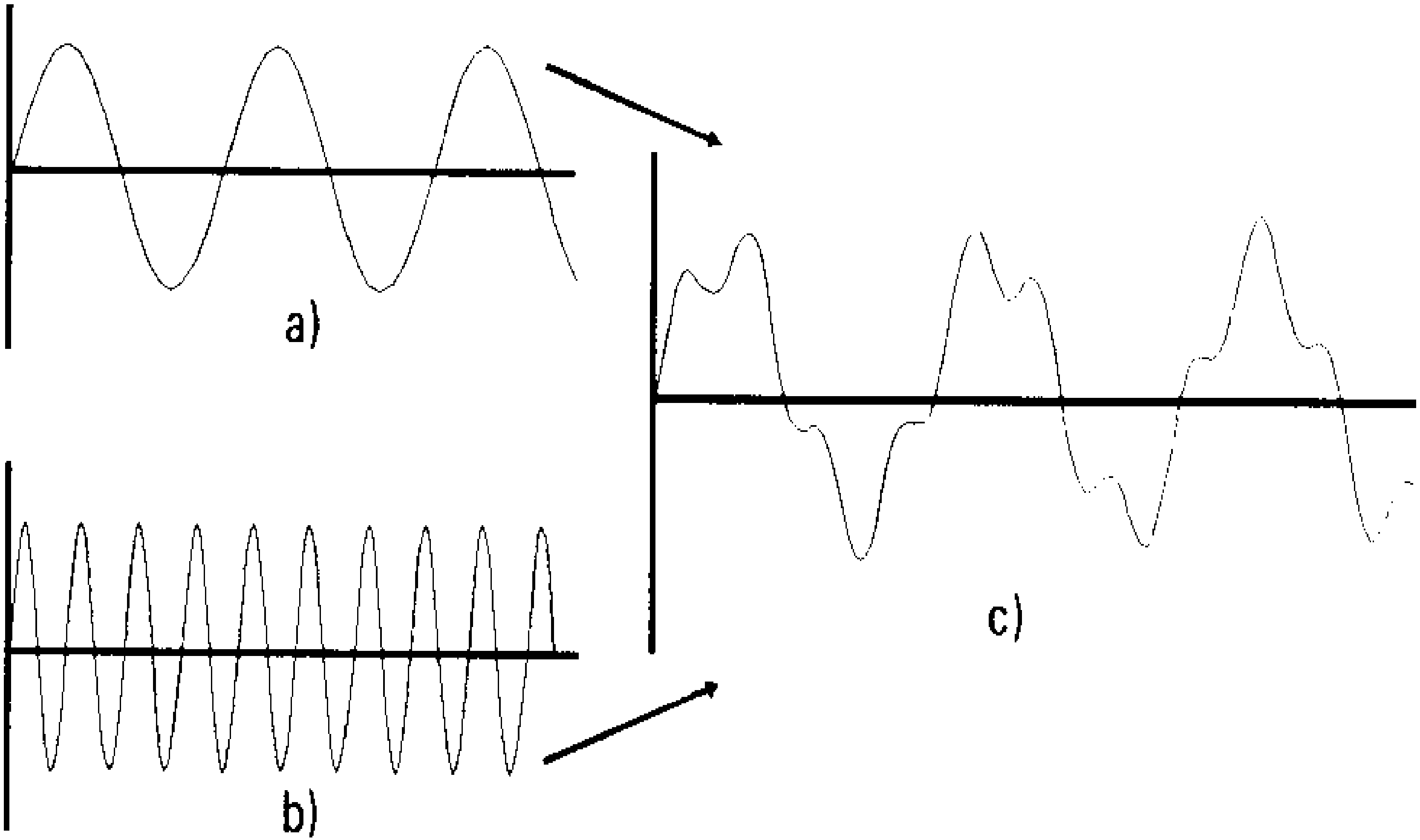
1 EMD/HHT (Hilbert Huang Transform)

2 MSE (Multiscale Entropy)

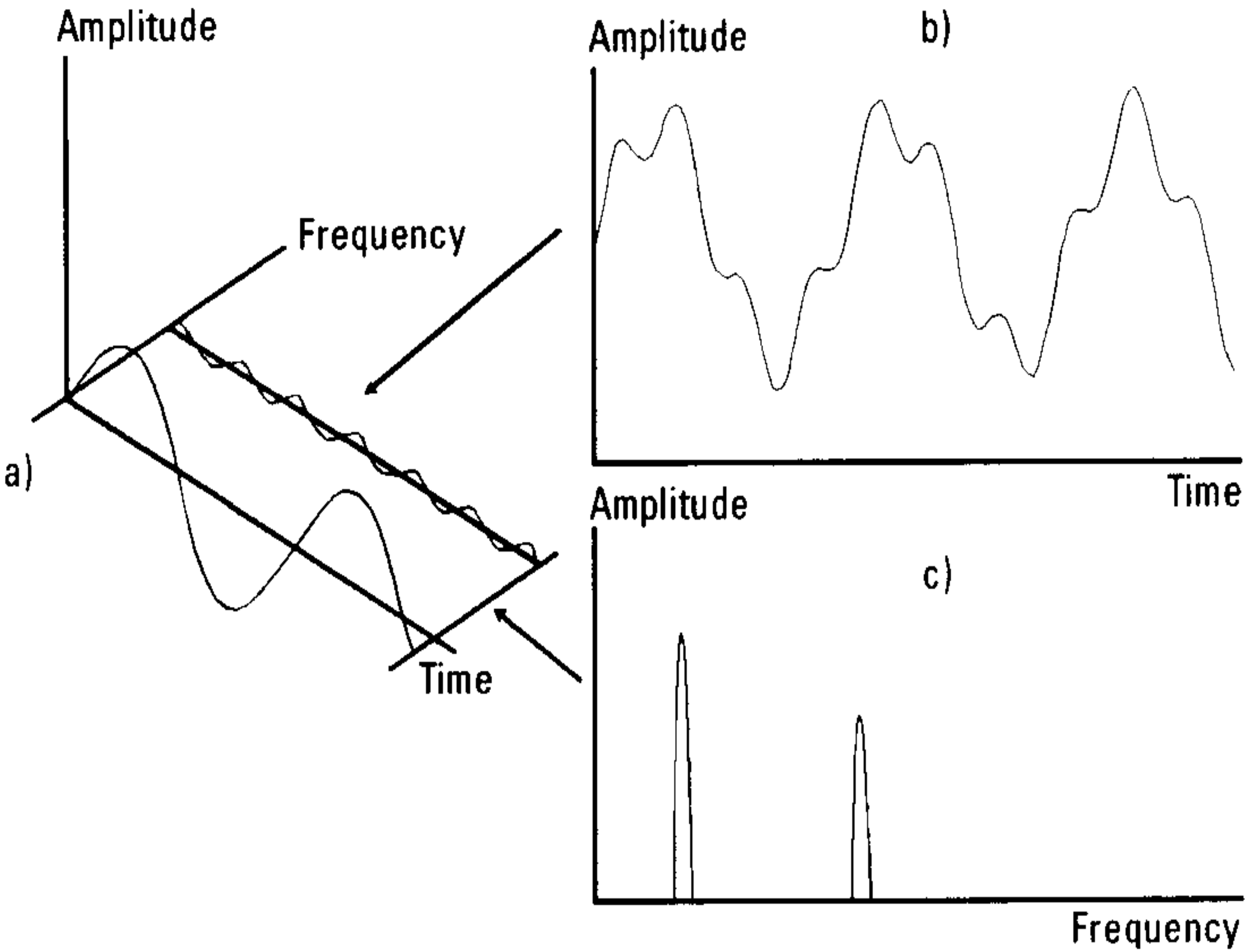
3 Torque Data Acquisition Analysis

4 Conclusion Remarks

Hybrid Signals

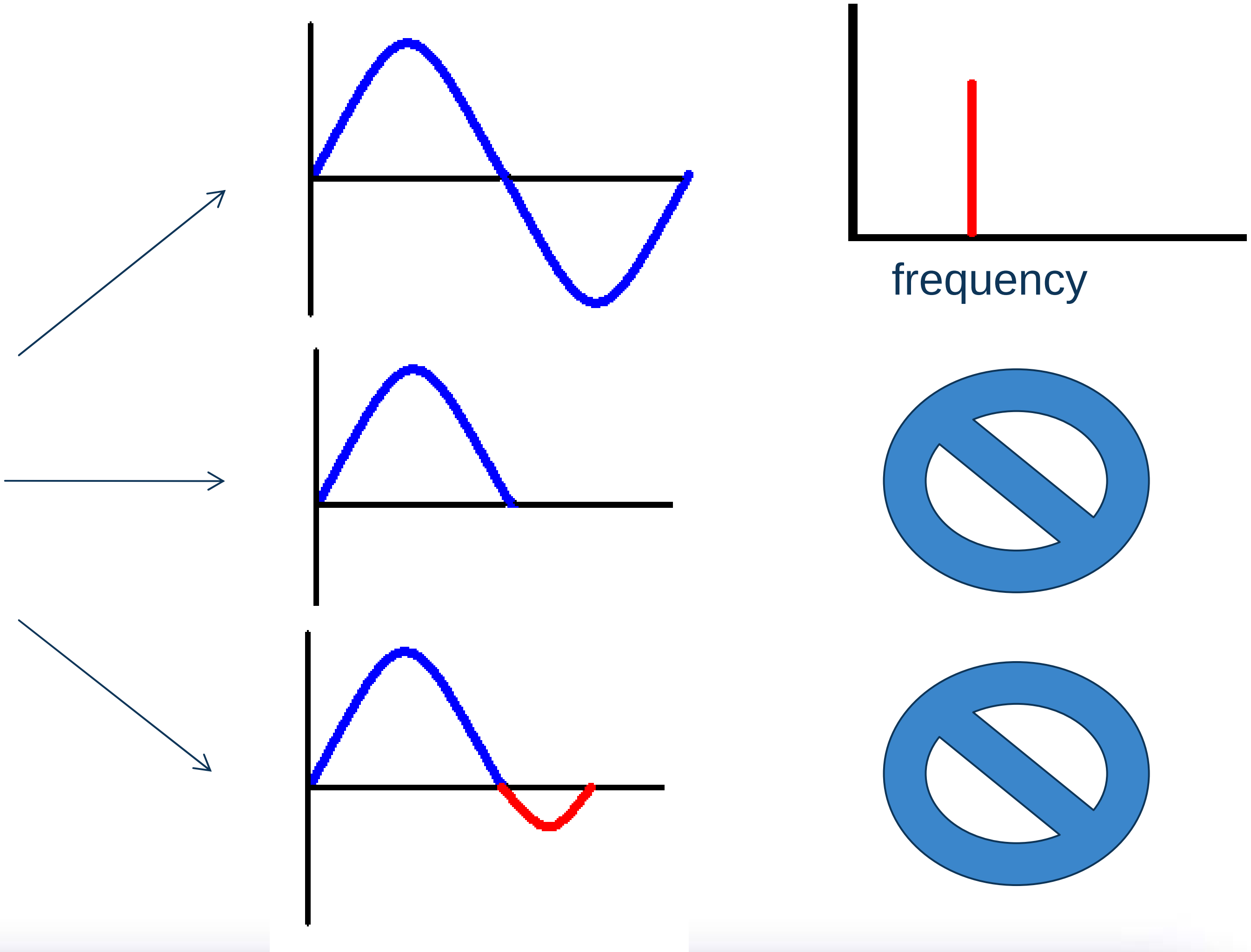


時域信號/頻率譜分析


Amplitude
Frequency
a)
Time
Amplitude
b)
Time
Amplitude
c)
Frequency

Fourier Condition

Fourier Transform

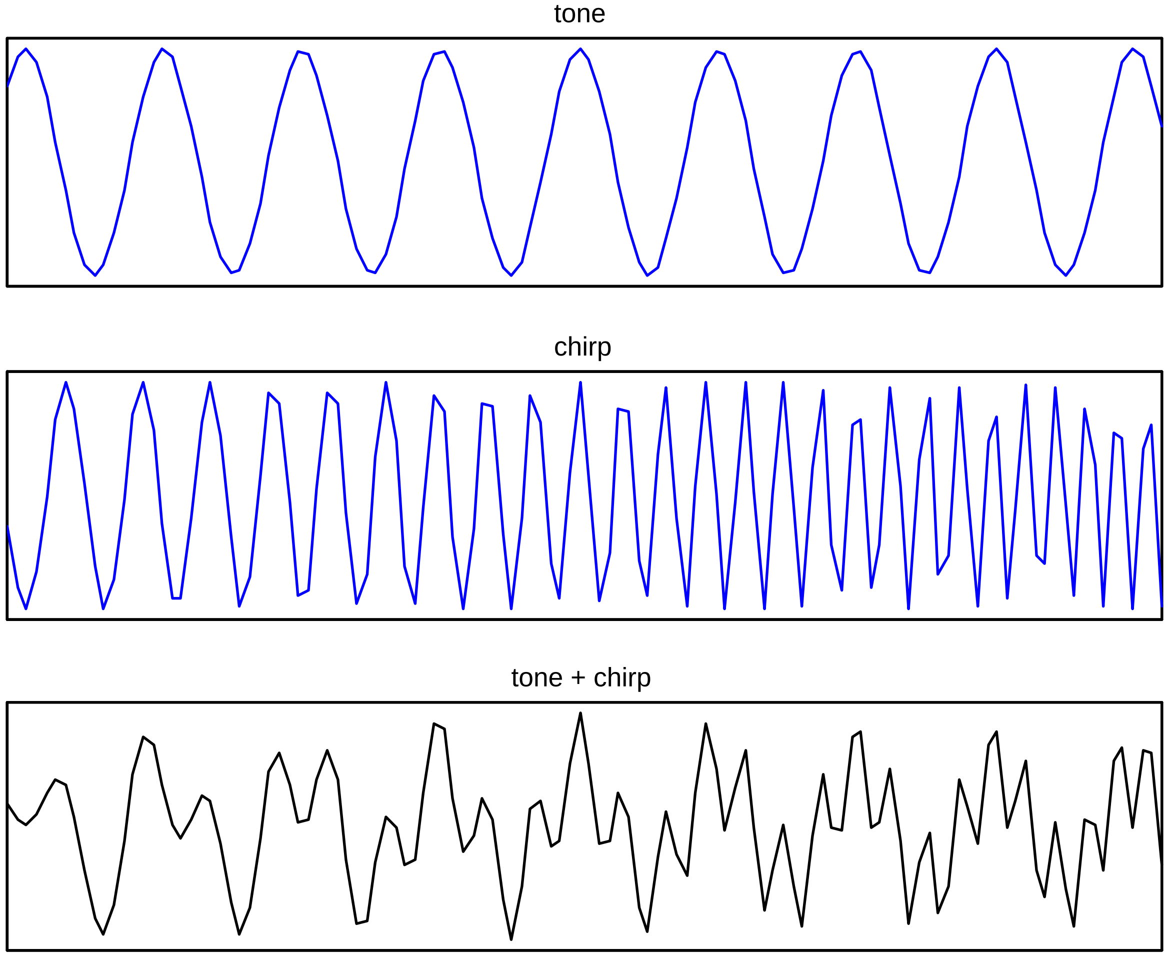


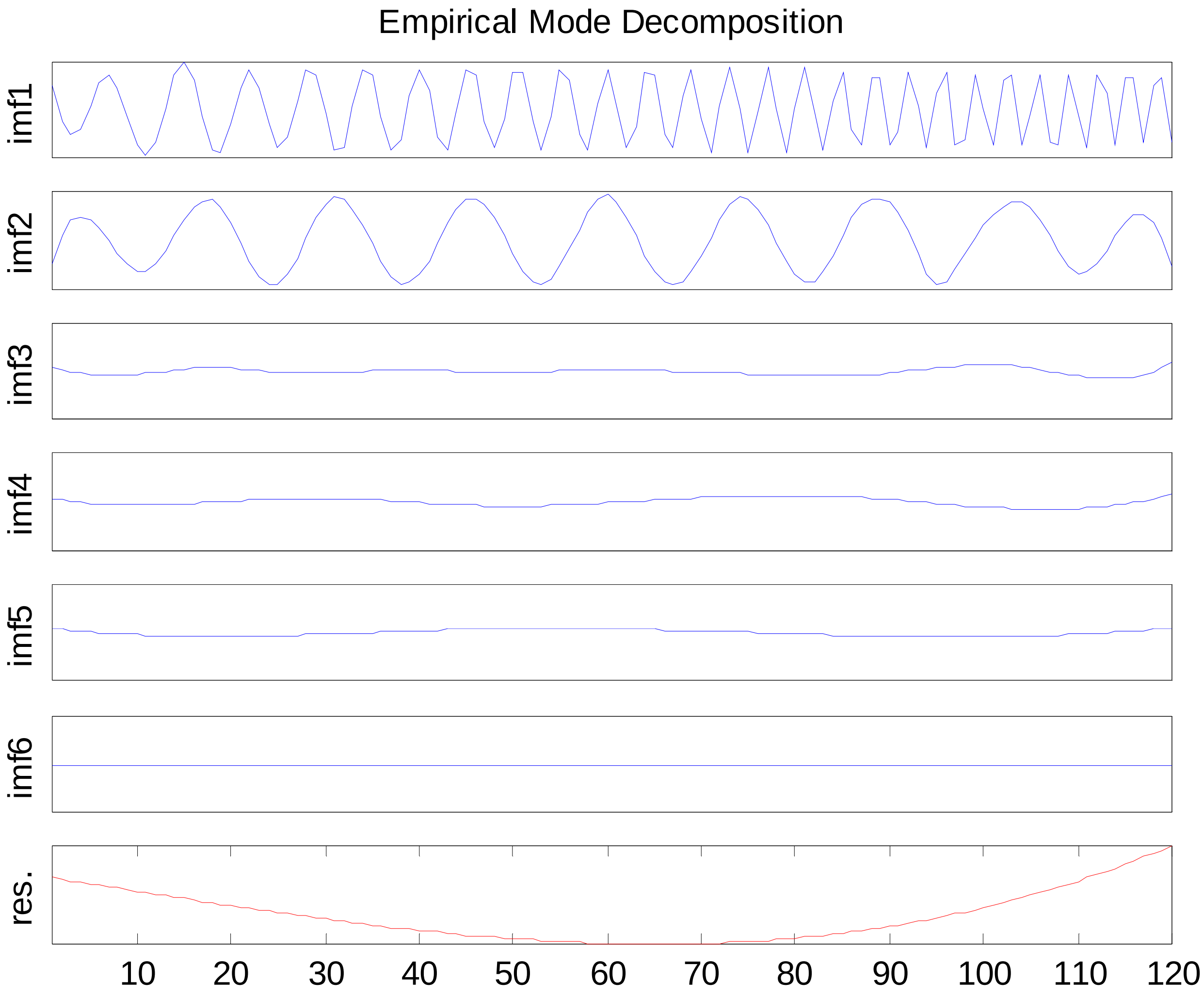
WHY 時頻分析

- 頻率為時間訊號的重要特徵，傳統用頻譜分析來了解一段時間內頻譜的分佈（ 傅利葉分析 ），但有時，我們更有興趣的是頻率隨時間變化的情形，如聲音語調的變化，機器運轉特異震動的頻率出現的時間其持續的長短。
- 了解頻率隨時間變化的情形，分析各種不同頻率隨時間變化的情形稱為**時頻分析**。時頻分析相較於頻譜分析多了頻率對時間的解析。利用時頻分析可以看出頻率隨著時間變化的情形。

EMD

- Empirical Mode Decomposition

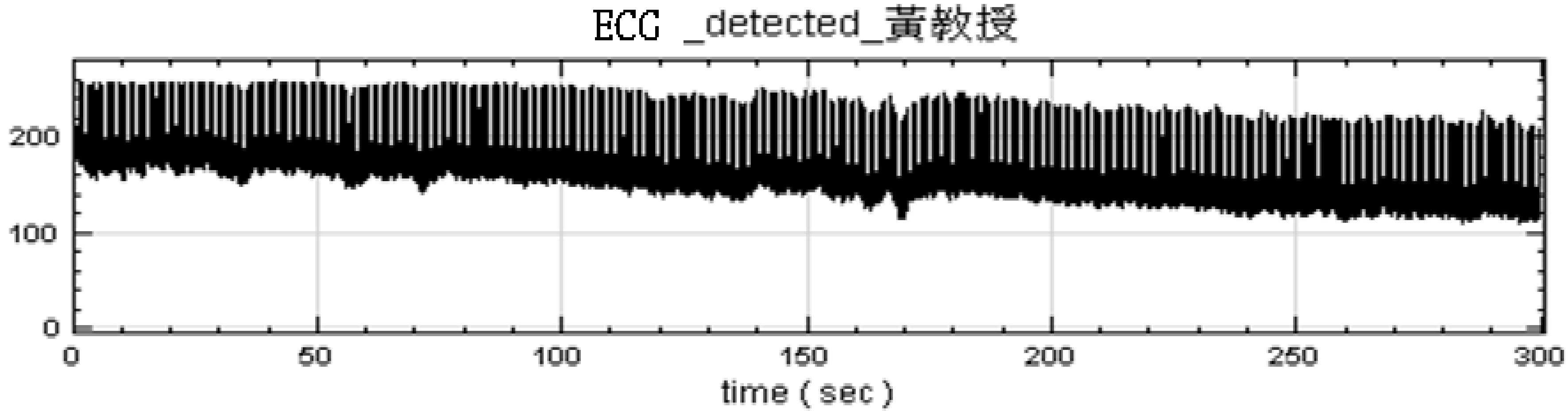

tone
chirp
tone + chirp



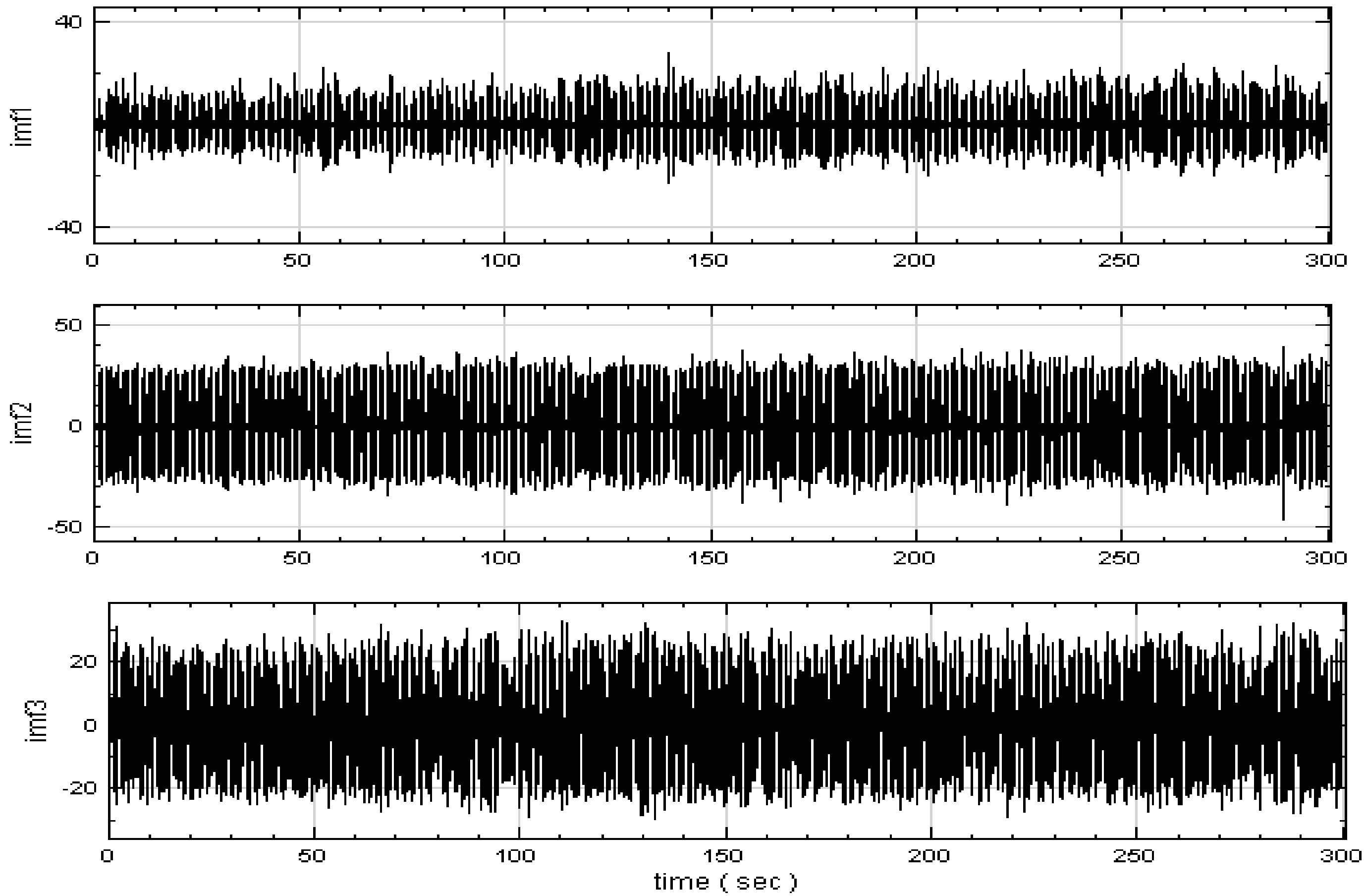
Empirical Mode Decomposition
imf1
imf2
imf3
imf4
imf5
imf6
res.
10
20
30
40
50
60
70
80
90
100
110
120

An Example

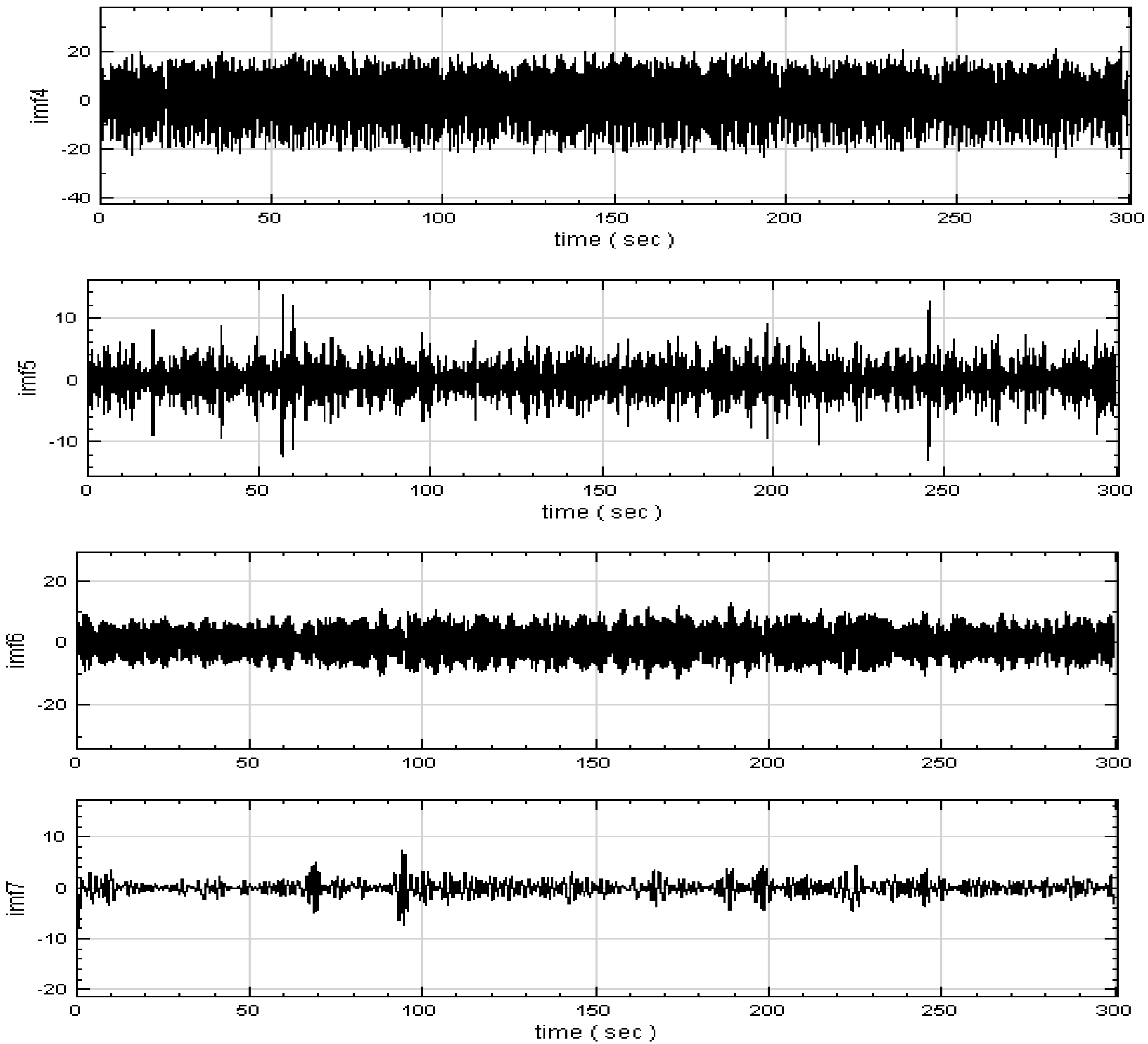
原始ECG訊號



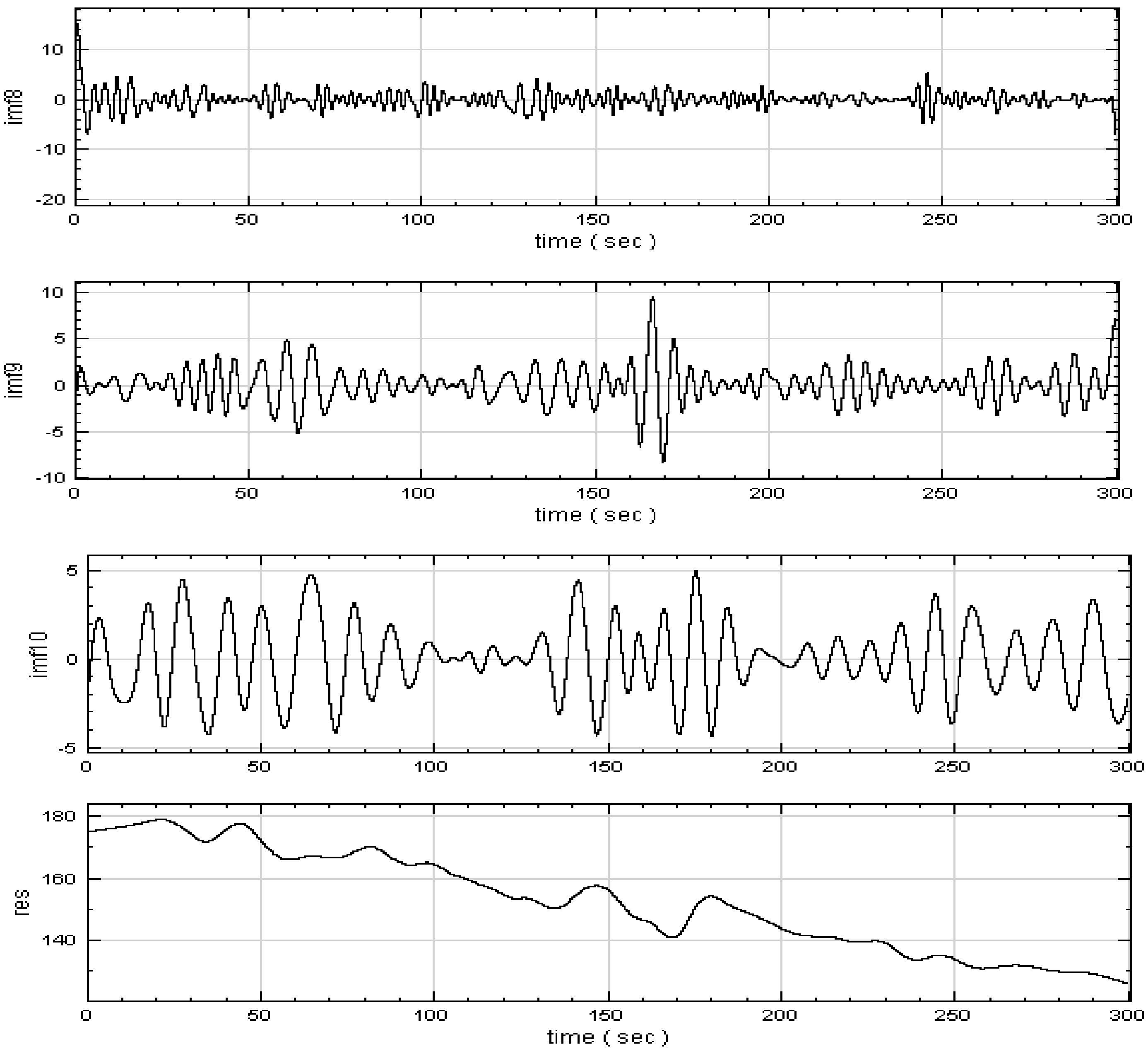
EMD分解



40
-40
imf1
0
50
100
150
200
250
300
50
0
-50
imf2
20
0
-20
imf3
time (sec)

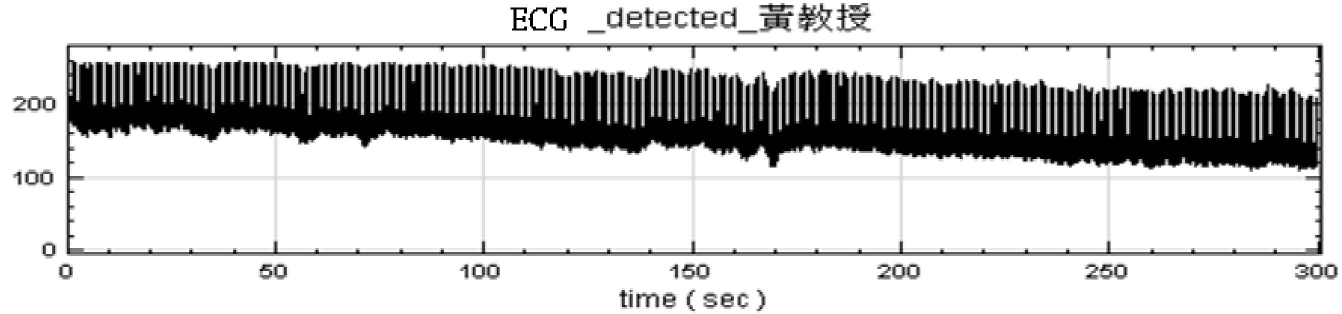


imf4
20
0
-20
-40
0
50
100
150
200
250
300
time (sec)
imf5
10
0
-10
0
50
100
150
200
250
300
time (sec)
imf6
20
0
-20
0
50
100
150
200
250
300
imf7
10
0
-10
-20
0
50
100
150
200
250
300
time (sec)

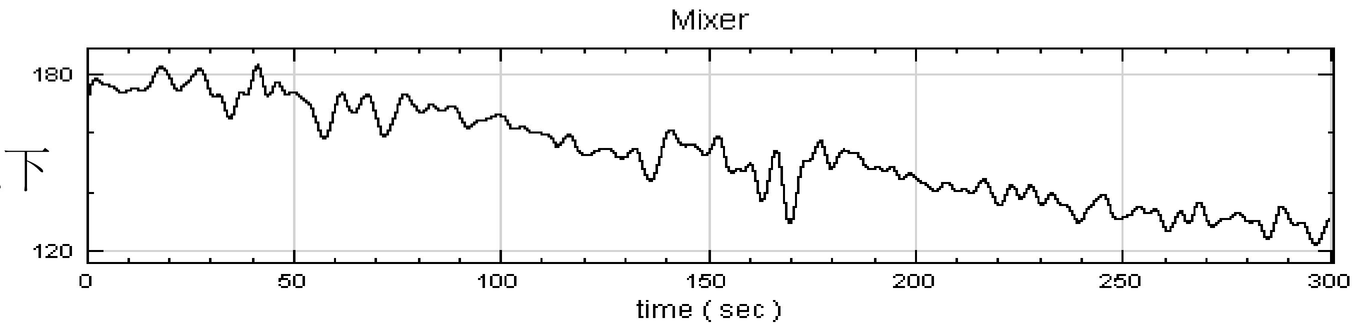

imf8
time (sec)
imf9
time (sec)
imf10
res
time (sec)

去除0.5Hz以下之IMF 8-IMF10

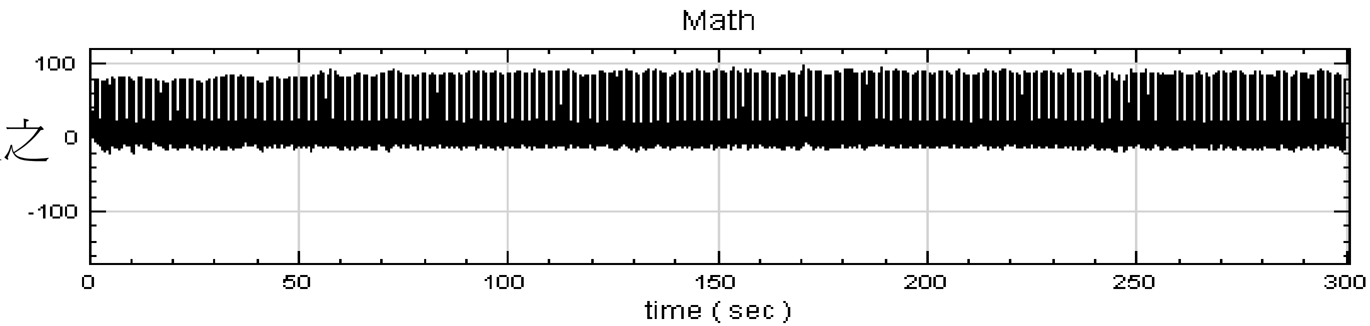
原始ECG



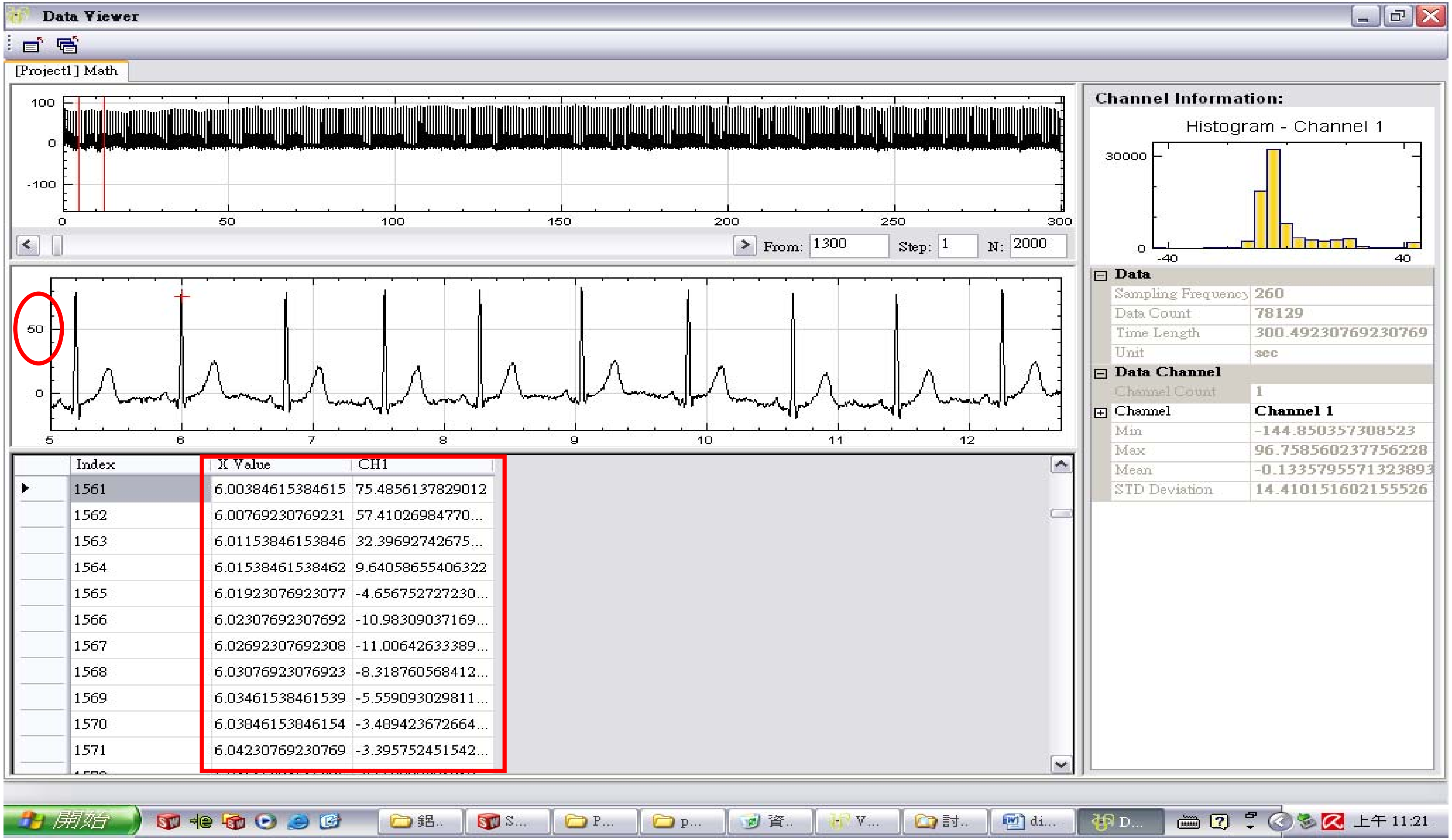
0.5HZ以下之IMF



相減後之新ECG



Heart Beat


Data Viewer
[Project1] Math
From: 1300
Step: 1
N: 2000
Channel Information:
Histogram - Channel 1
Data
Sampling Frequency 260
Data Count 78129
Time Length 300.49230769230769
Unit sec
Data Channel
Channel Count 1
Channel Channel 1
Min -144.850357308523
Max 96.758560237756228
Mean -0.1335795571323893
STD Deviation 14.410151602155526
Index
X Value
CH1
1561 6.00384615384615 75.4856137829012
1562 6.00769230769231 57.41026984770...
1563 6.01153846153846 32.39692742675...
1564 6.01538461538462 9.64058655406322
1565 6.01923076923077 -4.656752727230...
1566 6.02307692307692 -10.98309037169...
1567 6.02692307692308 -11.00642633389...
1568 6.03076923076923 -8.318760568412...
1569 6.03461538461539 -5.559093029811...
1570 6.03846153846154 -3.489423672664...
1571 6.04230769230769 -3.395752451542...

HHT/Instantaneous Frequency

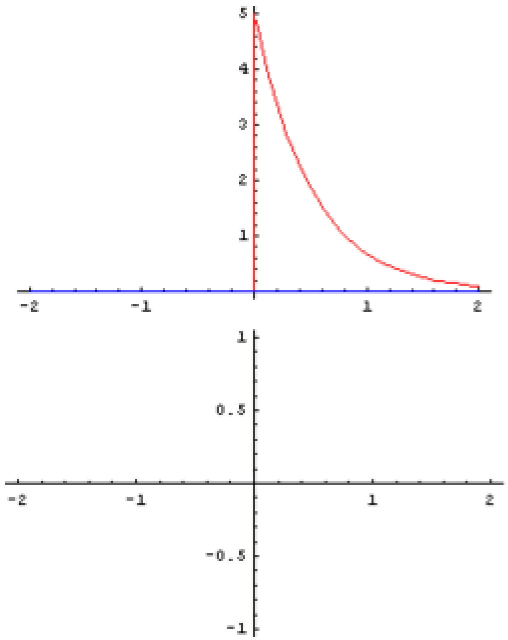
(Empirical Mode Decomposition) → **Hilbert Transform**

Hilbert Transform:

$$\tilde{x}(t) = \mathbf{H}\,[x(t)] = P\int_{-\infty}^{\infty} \frac{x(u)}{\pi(t-u)}\,du$$

$$\tilde{x}(t) = x(t) * \left(\frac{1}{\pi t}\right)$$

$$z(t) = x(t) + j\tilde{x}(t)$$



Instantaneous frequency

$$Y(t) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{X(\tau)}{t - \tau} d\tau$$

Y(t): Hilbert transform.

PV: Cauchy principal value.

X(t): arbitrary time series.

we can have an analytic signal, *Z*(*t*), as

$$Z(t) = X(t) + iY(t) = a(t)e^{i\theta t}$$

$$a(t) = \sqrt{X^2(t) + Y^2(t)}$$

$$\theta(t) = \tan^{-1}\left(\frac{Y(t)}{X(t)}\right)$$

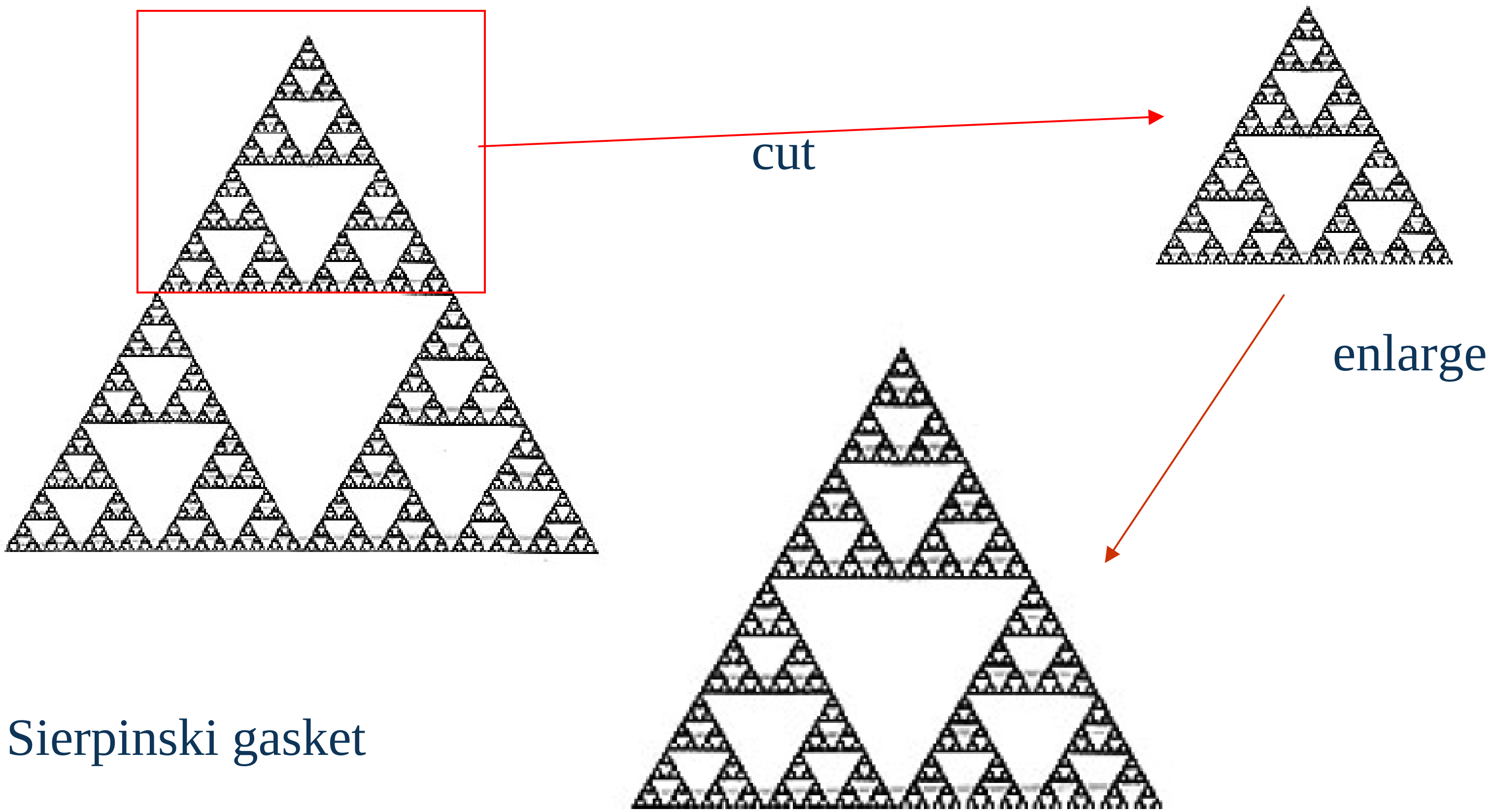
the instantaneous frequency as

$$w = \frac{d\theta(t)}{dt}$$

Outline

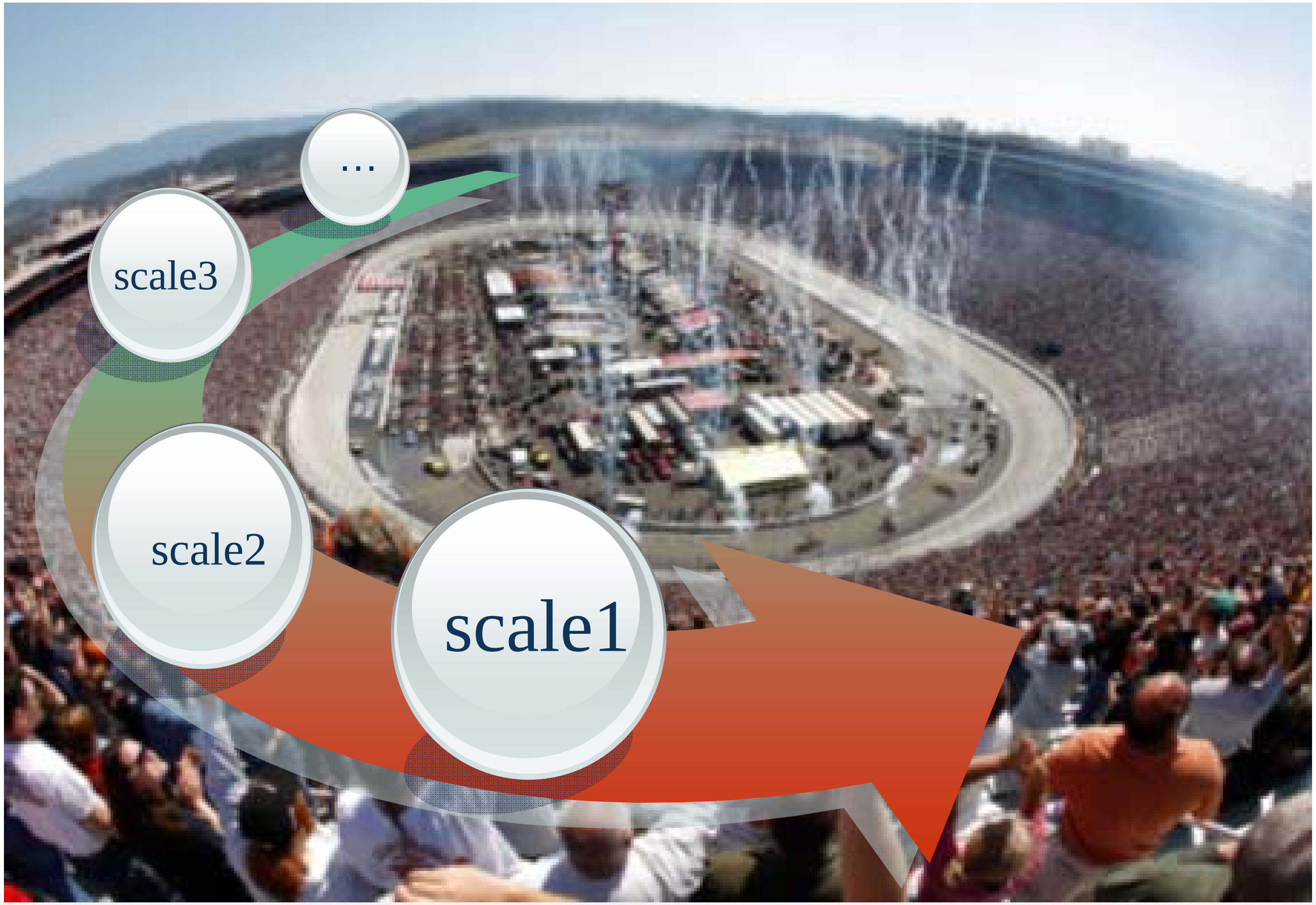
1. EMD/HHT
2. MSE (Multiscale Entropy) Fundamental
3. Torque Current Data Acquisition Analysis
4. Concluding Remarks

Self-similarity

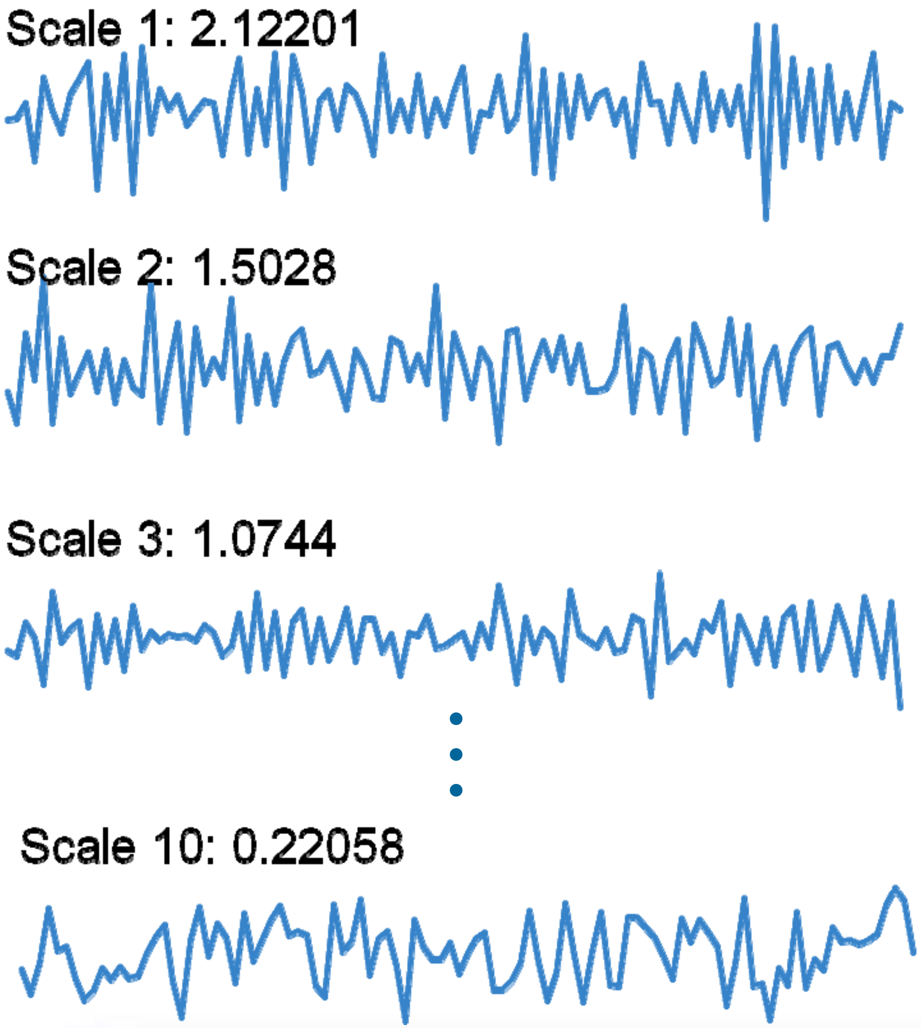


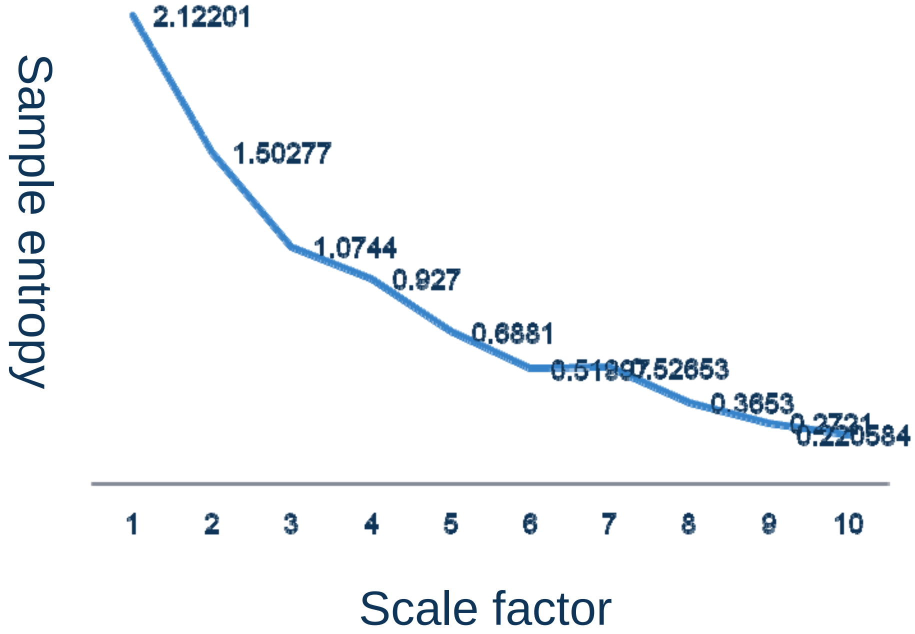
Sierpinski gasket

Crowd (chaos)

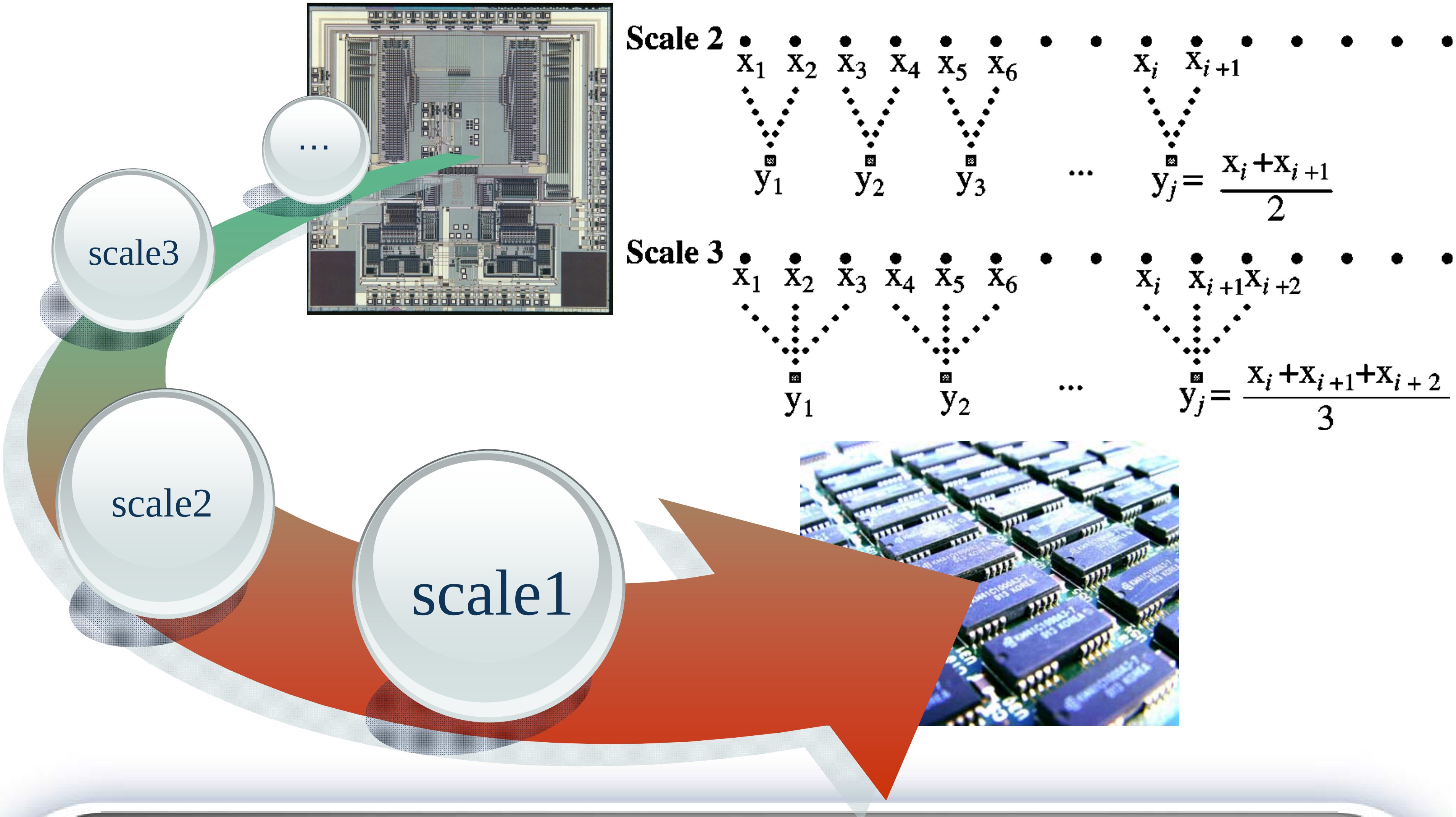


Violet noise

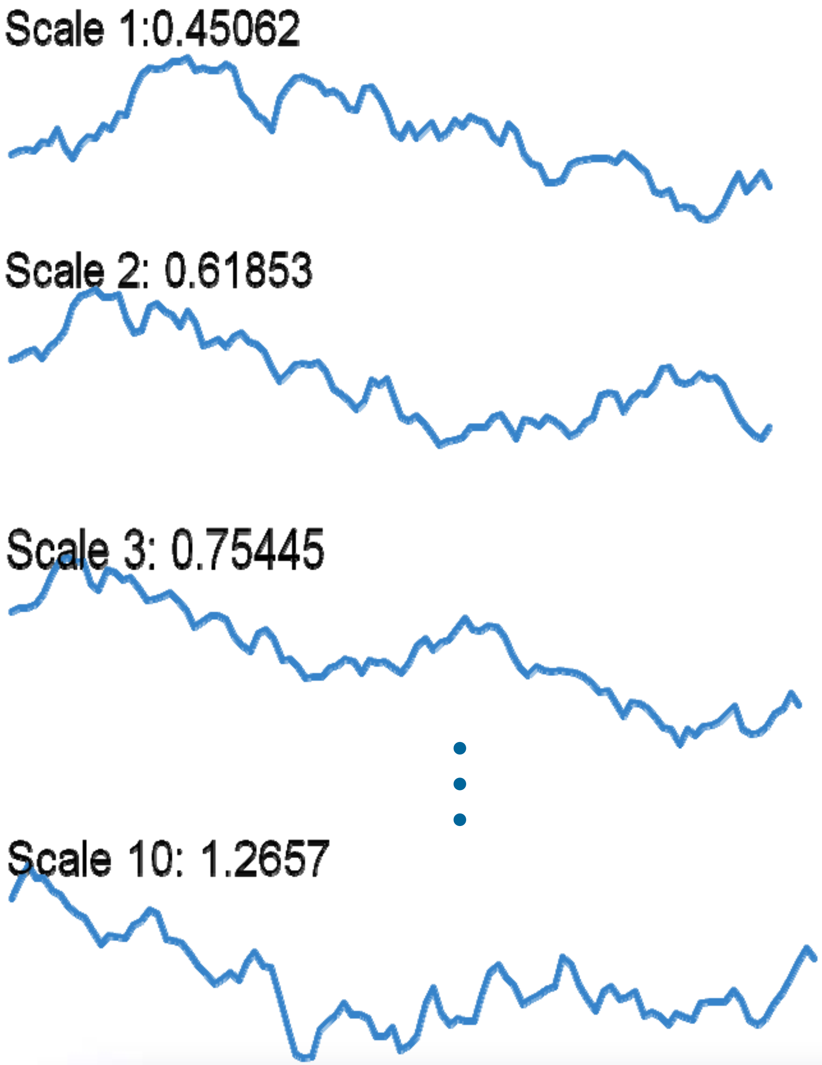


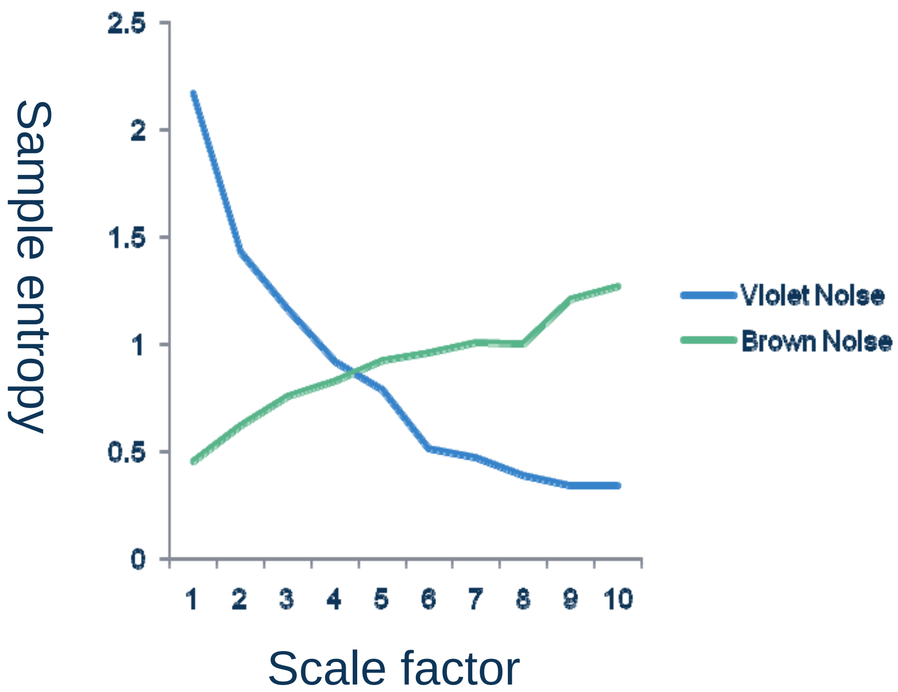


Circuit (complex)



Brown noise


Scale 1:0.45062
Scale 2: 0.61853
Scale 3: 0.75445
Scale 10: 1.2657


Sample entropy
Scale factor
Violet Noise
Brown Noise
2.5
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10

Outline

1 HHT (Hilbert Huang Transform) Fundamental

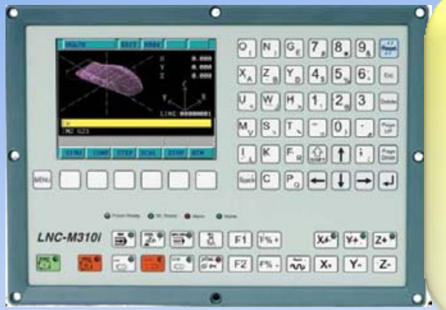
2 MSE (Multiscale Entropy) Fundamental

3 Torque Current Data Acquisition and Analysis

4 Concluding Remarks

實驗設備介紹

ASDA-A2 臺達電驅動器
- 內建電子凸輪功能，可以滿足多重軸動控制
- 由調機軟體可即時監視馬達運轉時多項變量



LNC-310i 寶元控制器
- 3軸同動，Pulse Command位置迴路控制
- 具有分段插補之功能

LS-177 海德漢光學尺
- Pulse command
- 提供AB相四倍解波，解析度0.25um

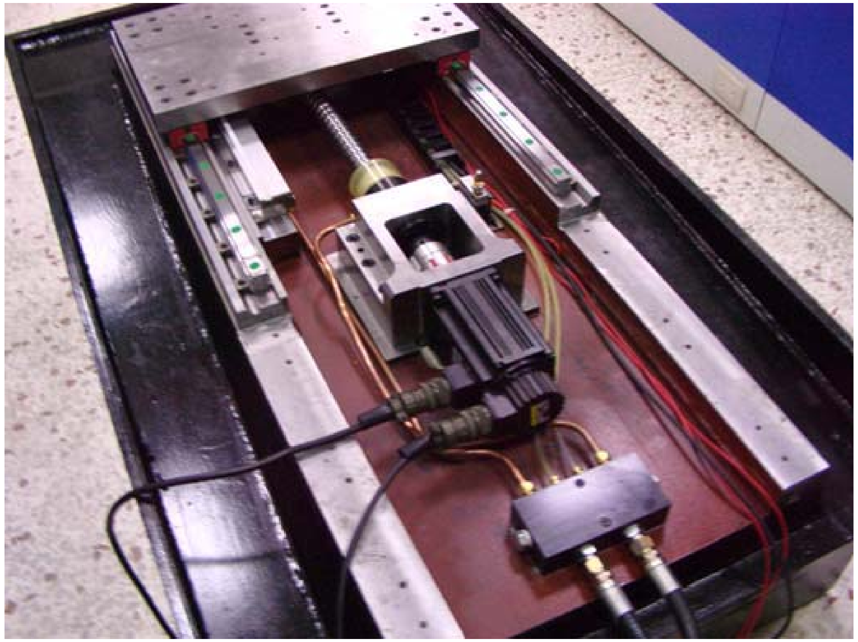
實驗架構-單螺帽導螺桿

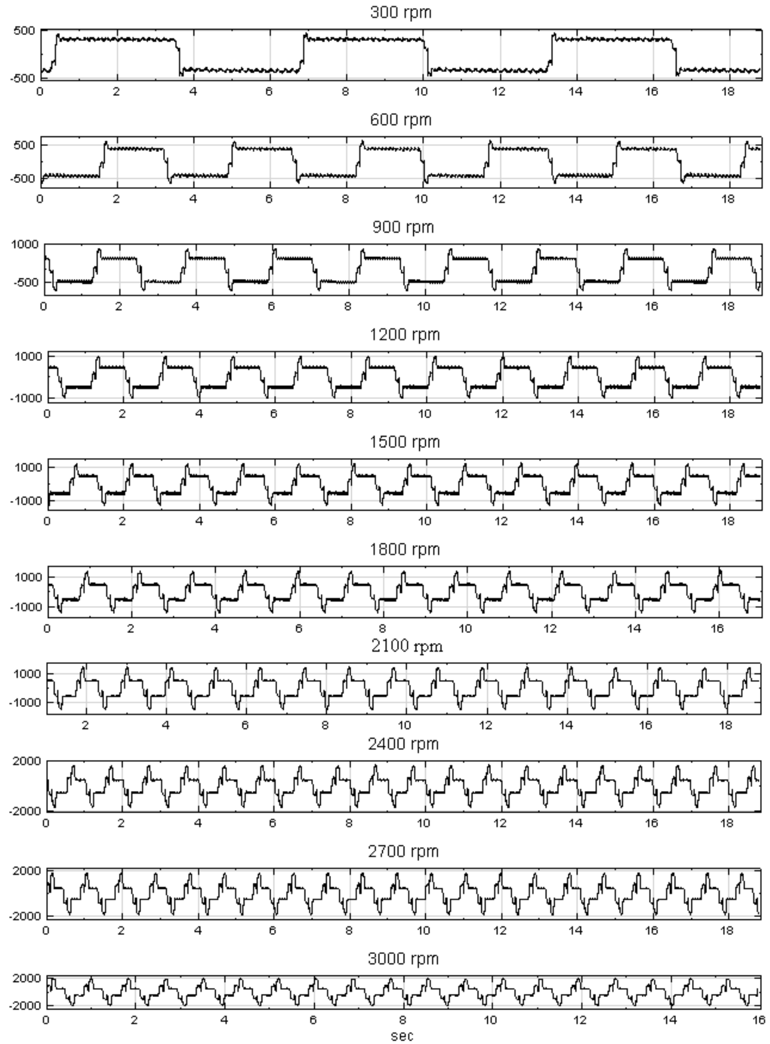
滾珠直徑 Ball Diameter	6.35mm
螺桿根徑 Root Diameter	30.91mm
最大動負荷 Dynamic Load	3750kgf
最大靜負荷 Static Load	9542kgf
挫曲負荷 Buckling Load	70288kgf

與最大動負荷之比例	實際預壓之量值
2%	75kgf
3%	113kgf
4%	150kgf
5%	188kgf
6%	250kgf

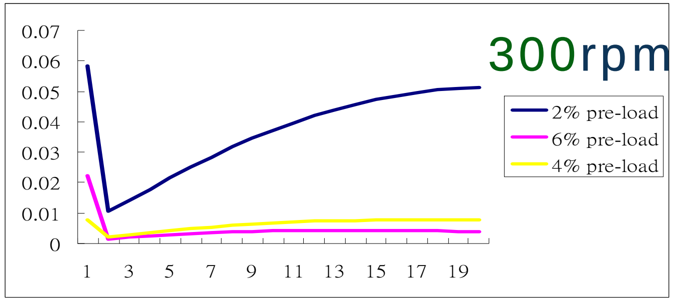
Experimental tests

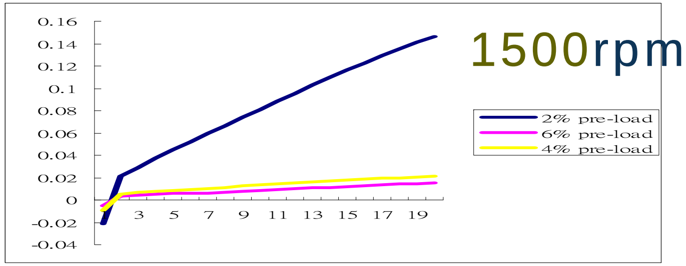
The table is commanded for the traveling distance of 270mm with reciprocating movement. Driven by a servo motor followed by a coupler and single nut ball screw table with different preloads.

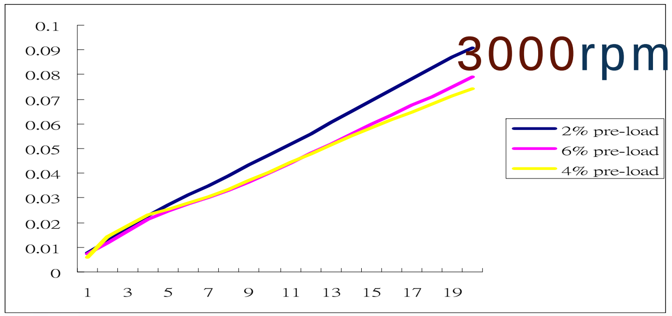


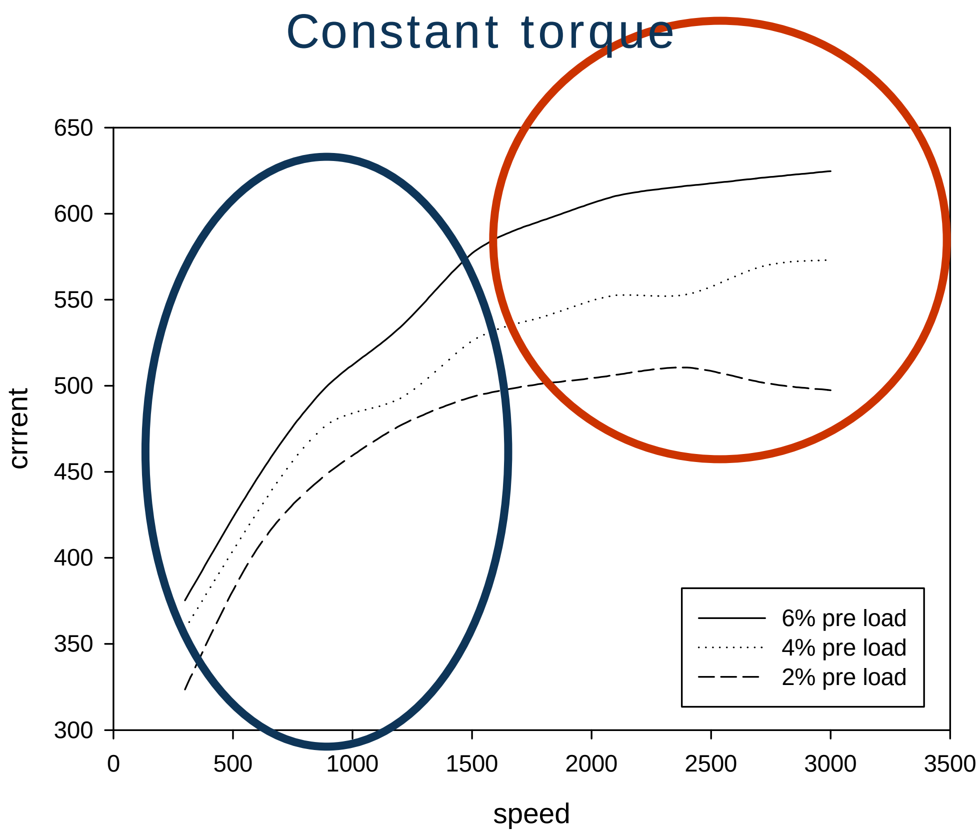


Steady state

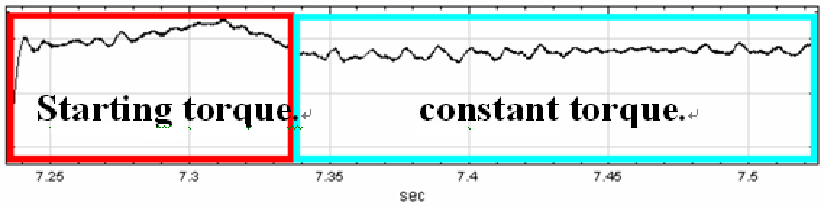


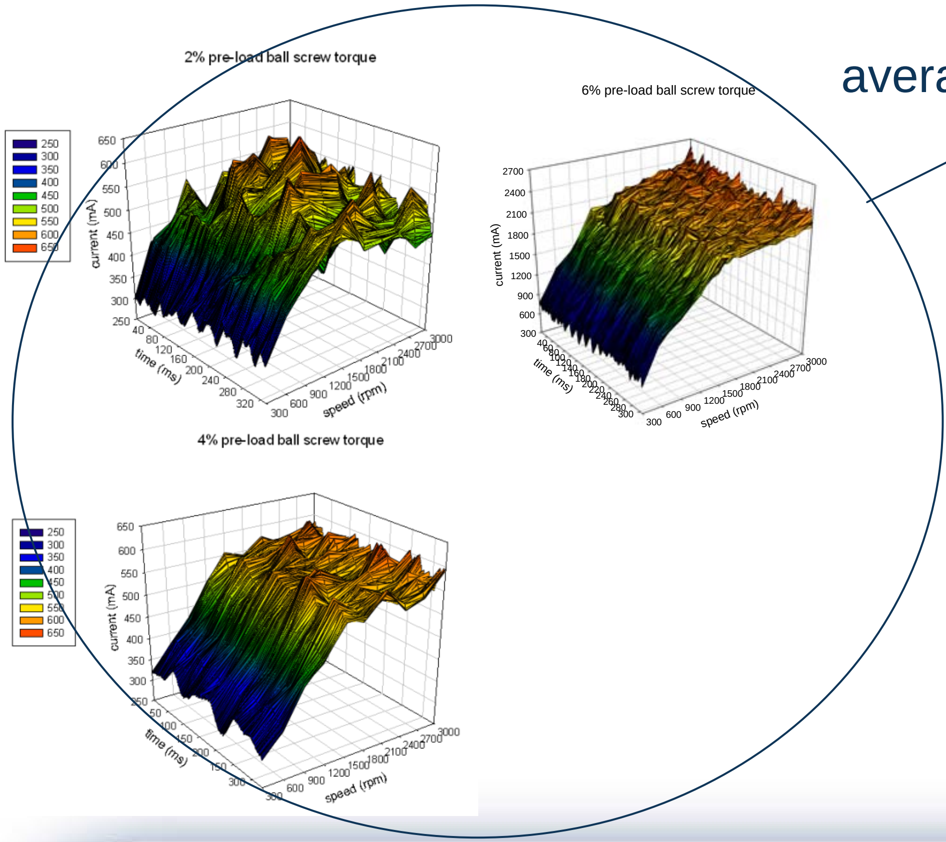






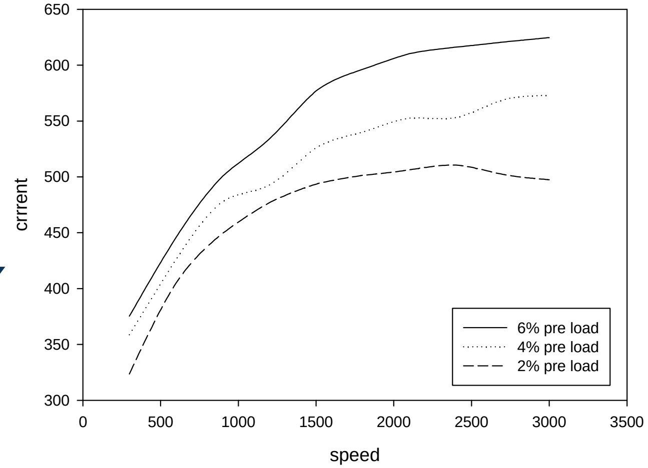
Data observe



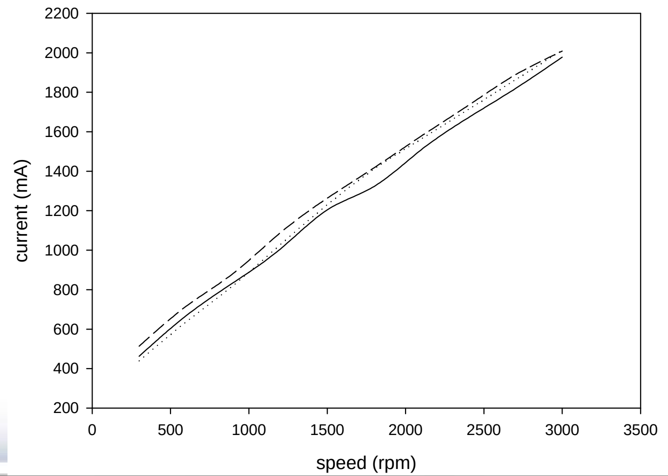


average

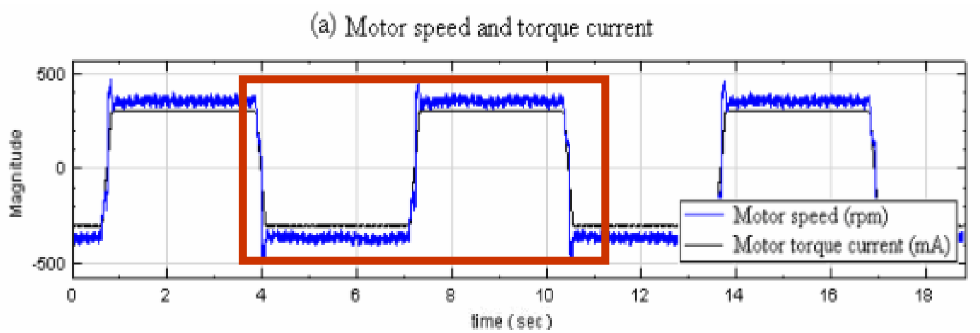
Constant torque

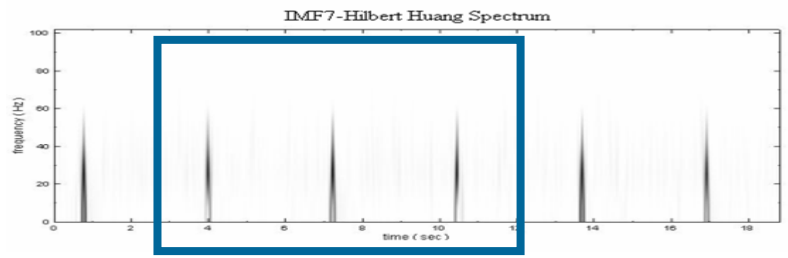


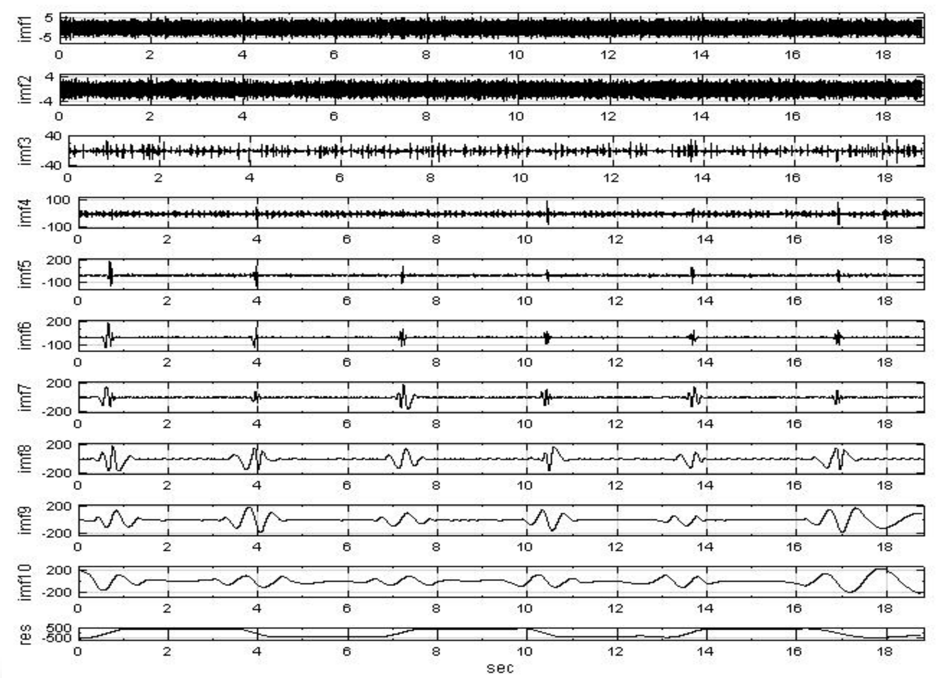
Starting torque

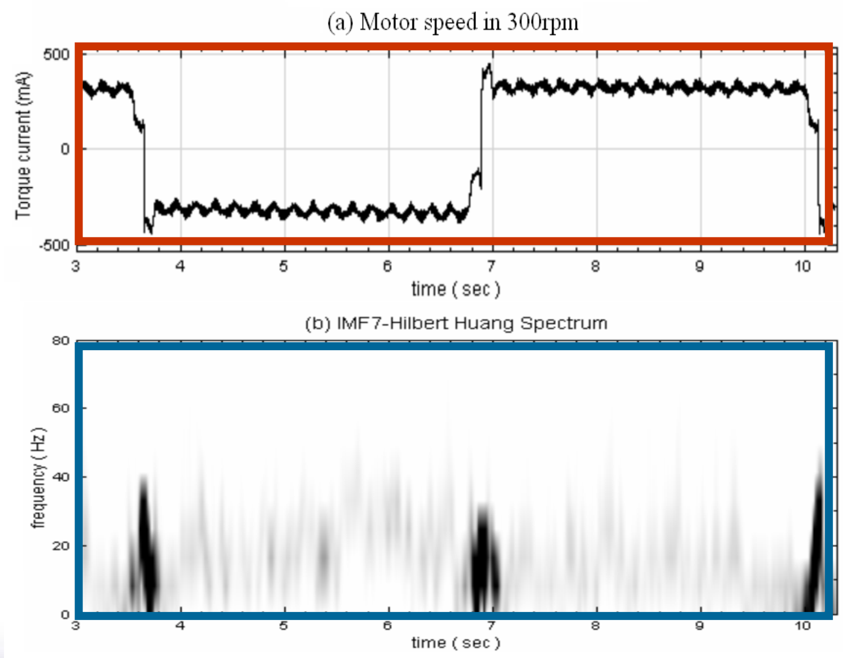


HHT process

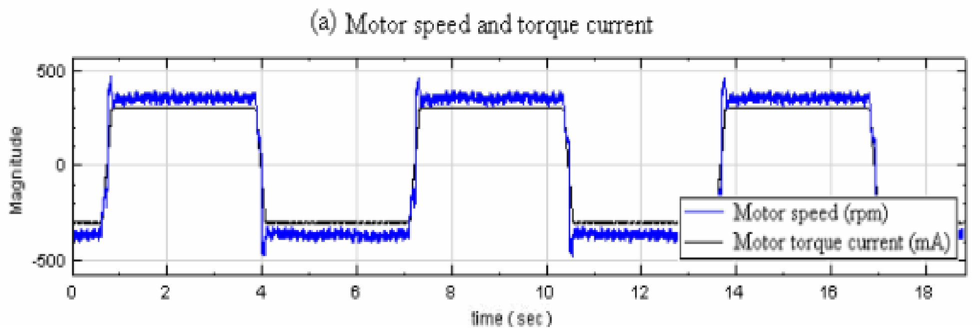

(a) Motor speed and torque current
Magnitude
time (sec)
Motor speed (rpm)
Motor torque current (mA)

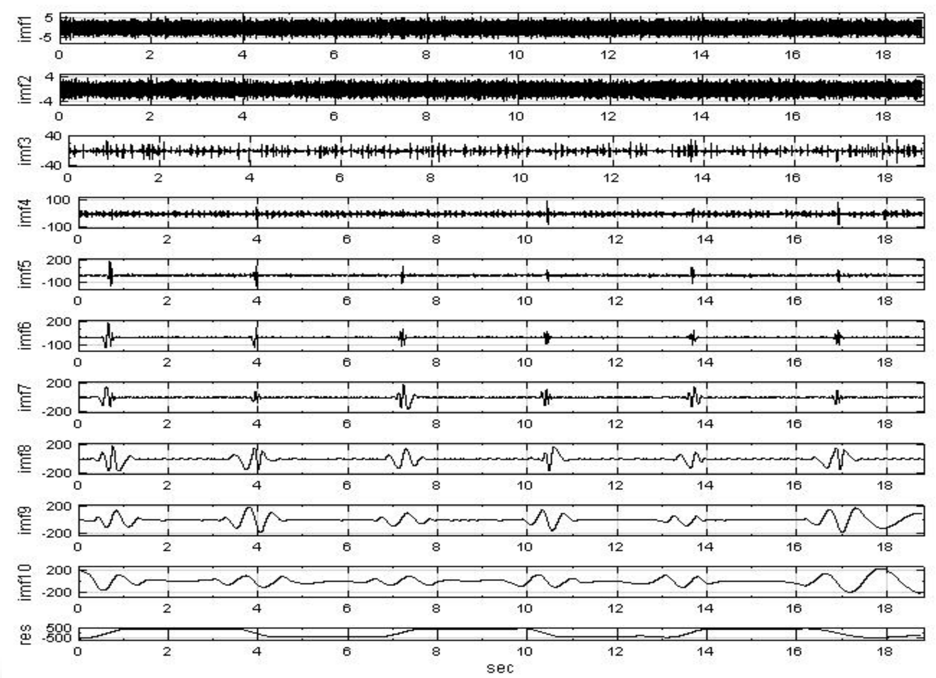

IMF7-Hilbert Huang Spectrum

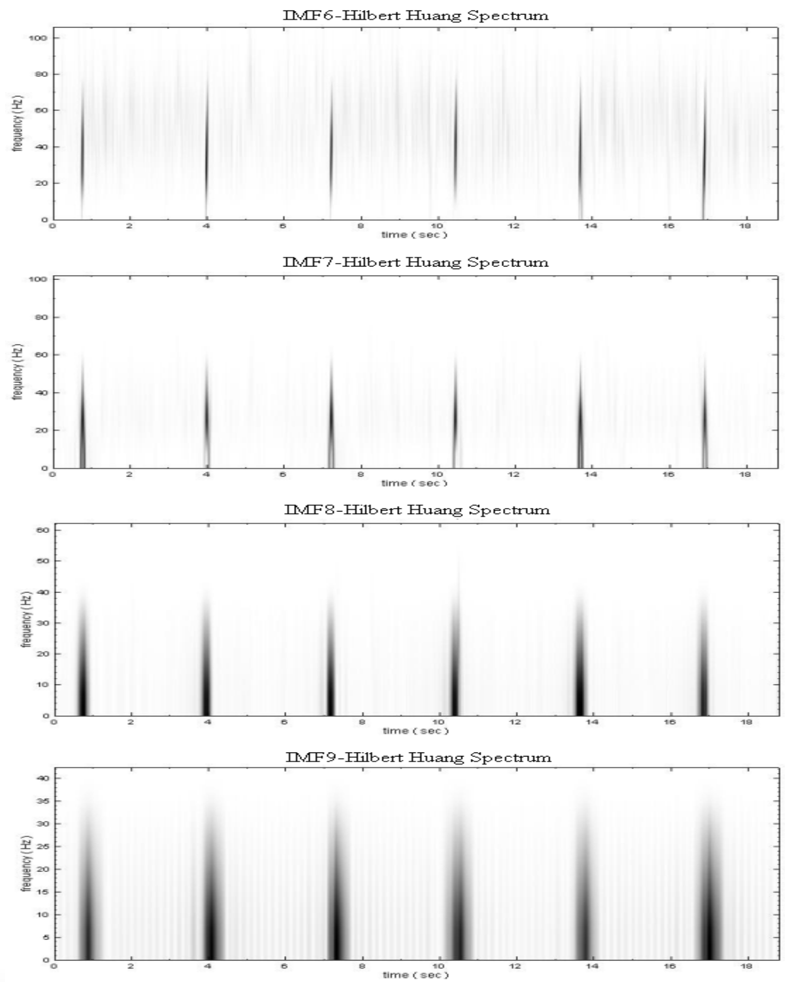

imf1
imf2
imf3
imf4
imf5
imf6
imf7
imf8
imf9
imf10
res
sec


(a) Motor speed in 300rpm
Torque current (mA)
time (sec)
(b) IMF7-Hilbert Huang Spectrum
frequency (Hz)
time (sec)

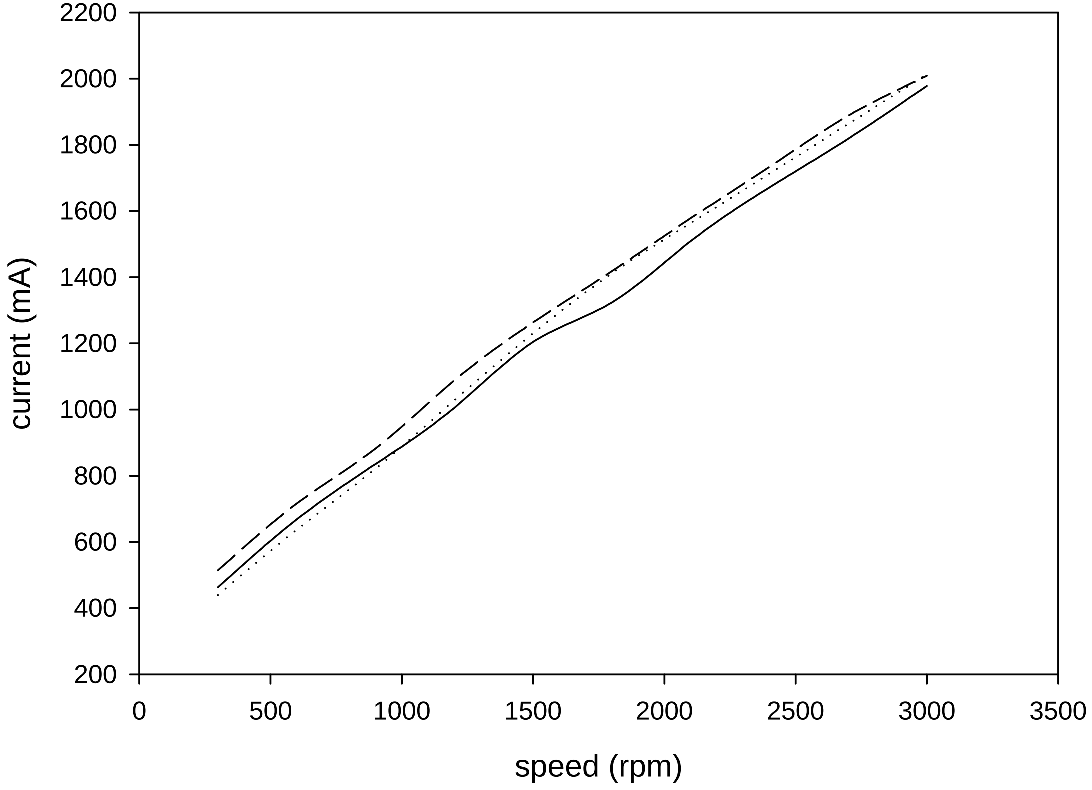
HHT process


(a) Motor speed and torque current
Magnitude
500
0
-500
0 2 4 6 8 10 12 14 16 18
time (sec)
Motor speed (rpm)
Motor torque current (mA)


imf1
imf2
imf3
imf4
imf5
imf6
imf7
imf8
imf9
imf10
res
sec

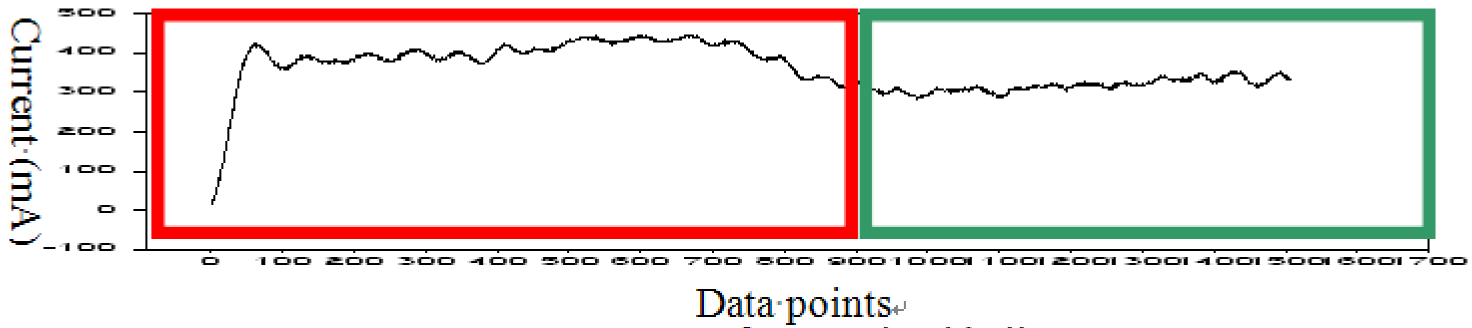

IMF6-Hilbert Huang Spectrum
IMF7-Hilbert Huang Spectrum
IMF8-Hilbert Huang Spectrum
IMF9-Hilbert Huang Spectrum
frequency (Hz)
time (sec)

- In Figure we enlarged the torque currents marked in red and green from the original torque current history and followed the IMF4 of EMD process. The red regime implies the time span of starting torque current whereas the green regime indicates the time span of constant rpm for quasi-steady-state torque current. The spiky amplitude for starting torque of 2 %, 4 %, and 6 % preloads in red is approximately 32mA, 64mA, and 96mA, respectively. This correlates to the specific time duration for instantaneous required torque of different preloads in Figure 7(b).

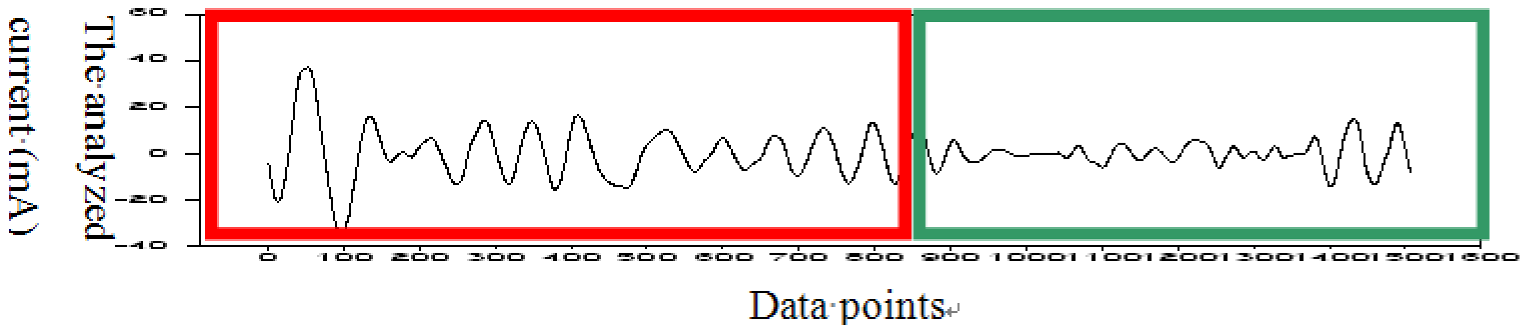

2200
2000
1800
1600
1400
1200
1000
800
600
400
200
current (mA)
0
500
1000
1500
2000
2500
3000
3500
speed (rpm)

IMFs Identify

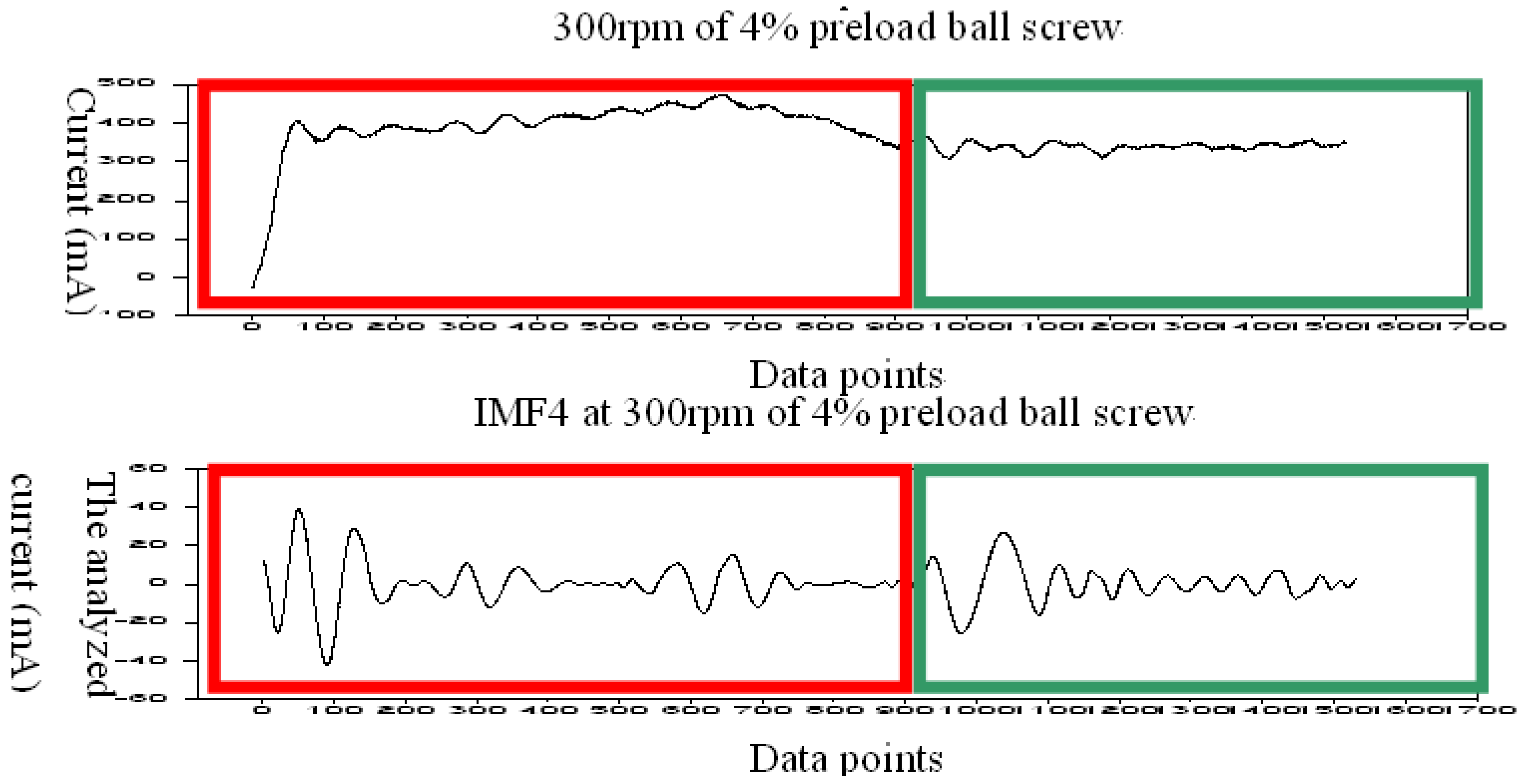
300rpm of 2% preload ball screw



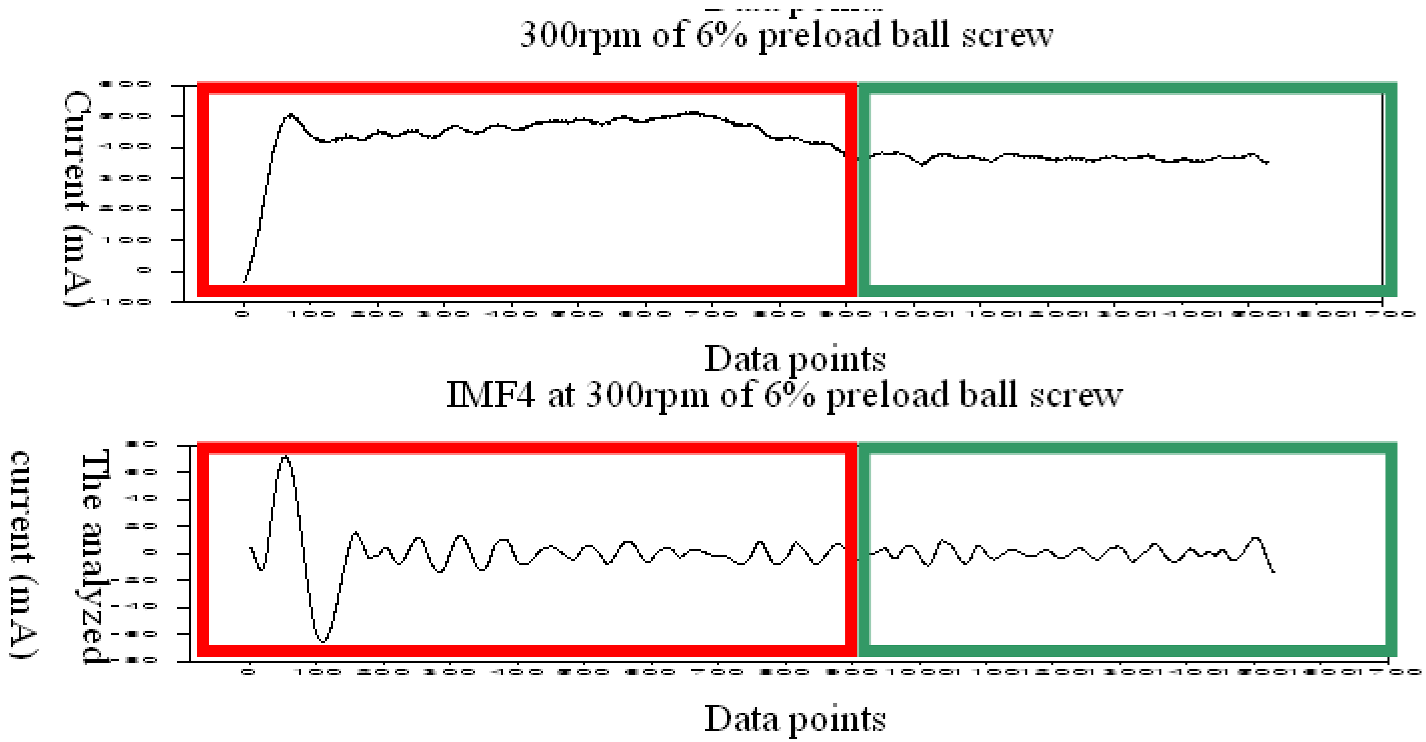
IMF4 at 300rpm of 2% preload ball screw



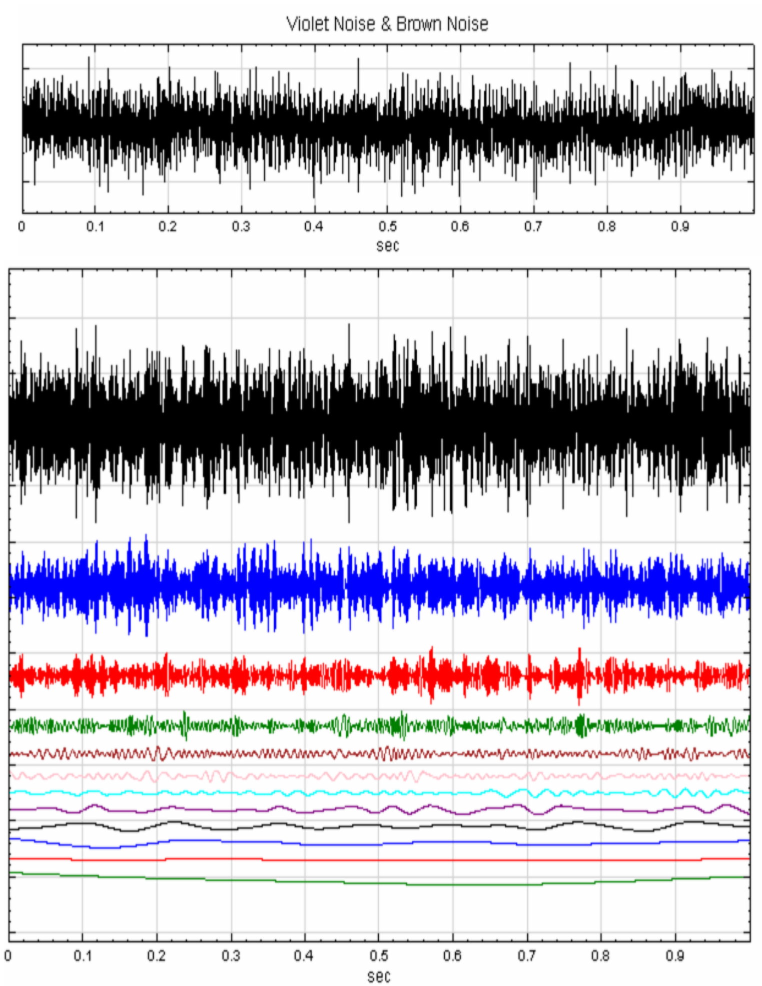
IMFs Identify

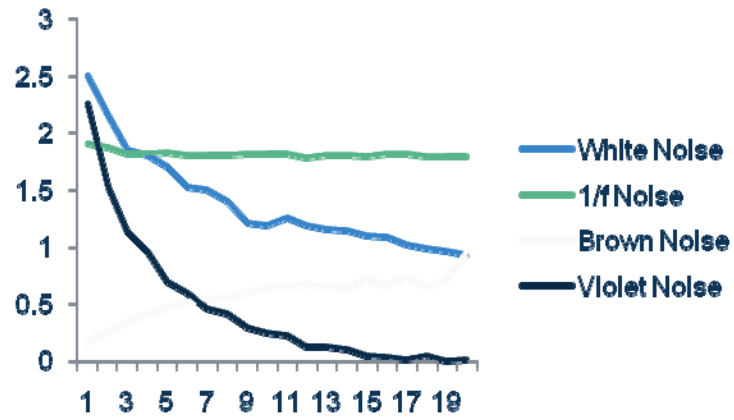


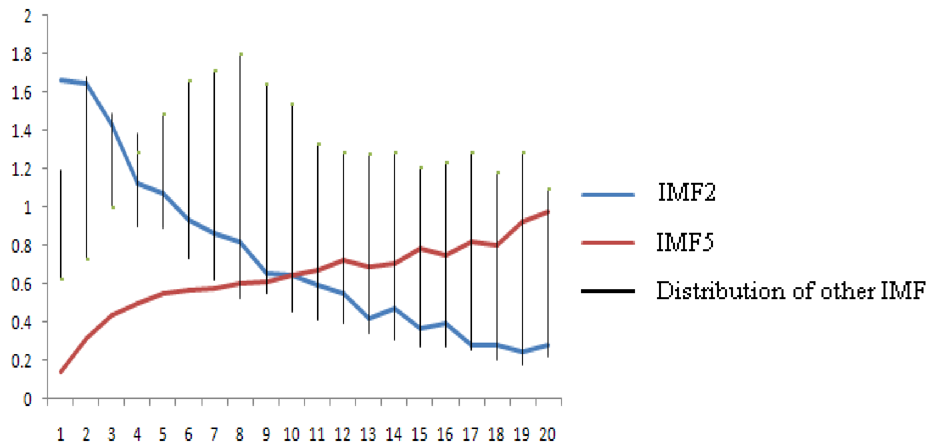
IMFs Identify



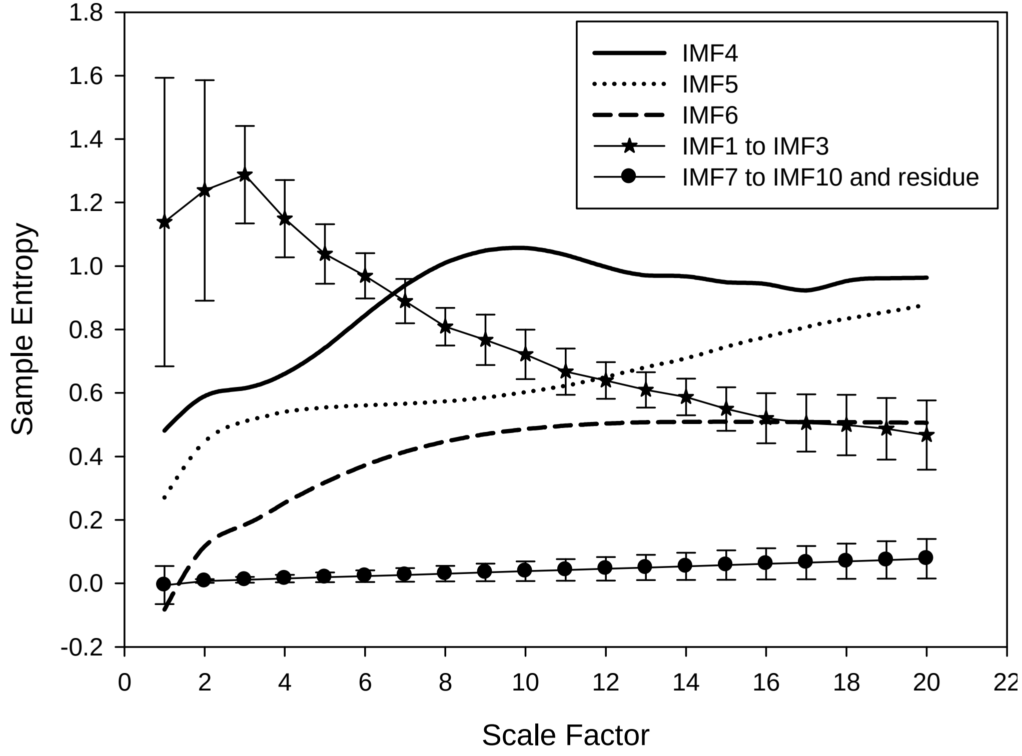
HHT&MSE

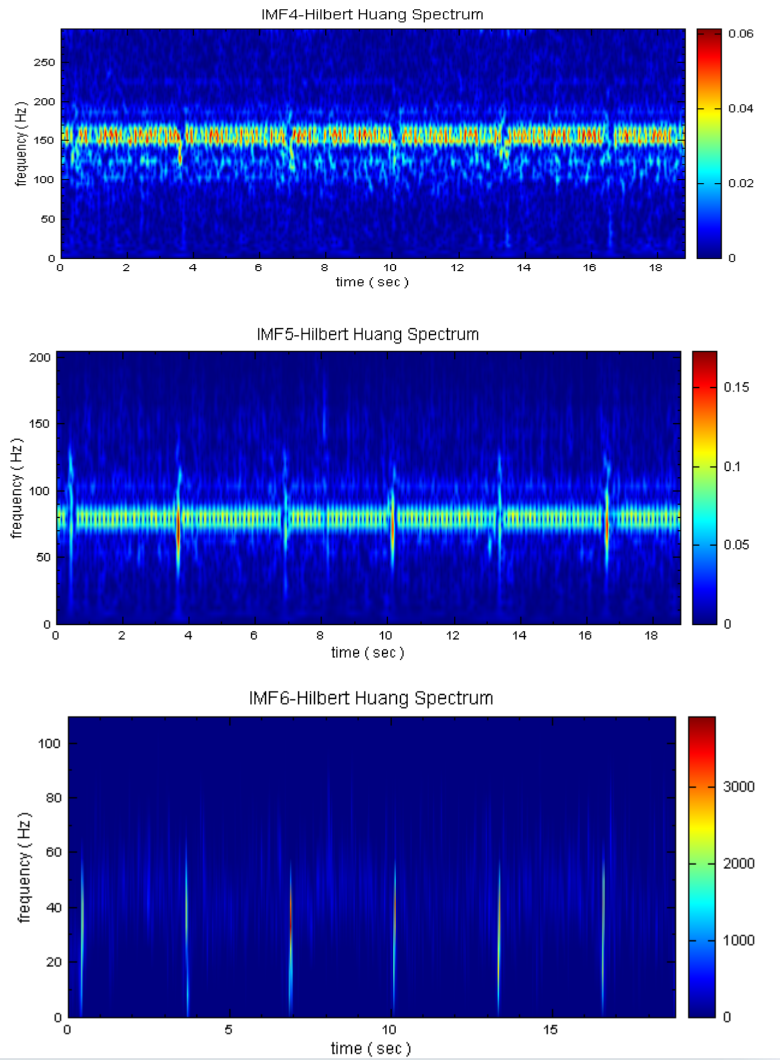

Violet Noise & Brown Noise
sec
sec


White Noise
1/f Noise
Brown Noise
Violet Noise

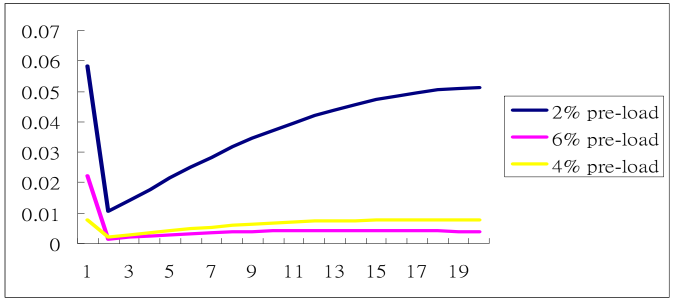

IMF2
IMF5
Distribution of other IMF

IMFs Identify

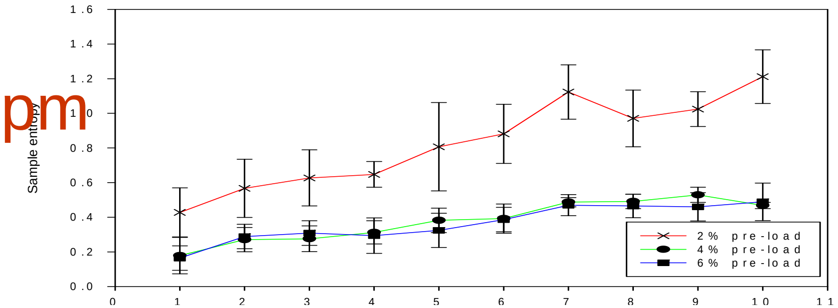


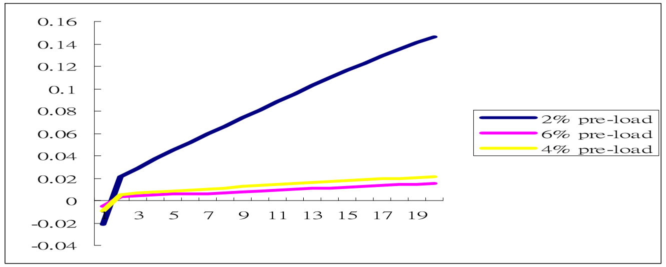


MSE

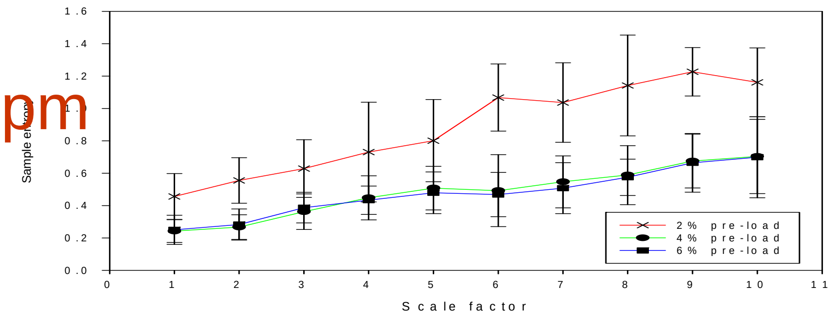


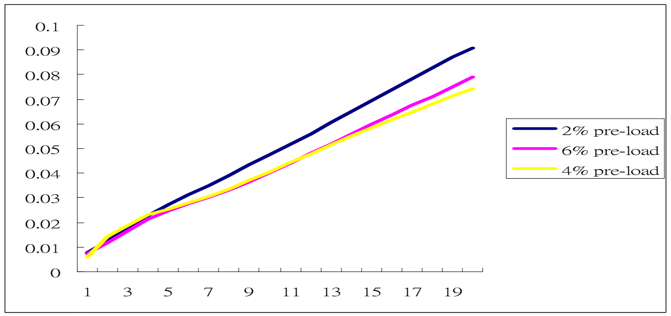
300rpm



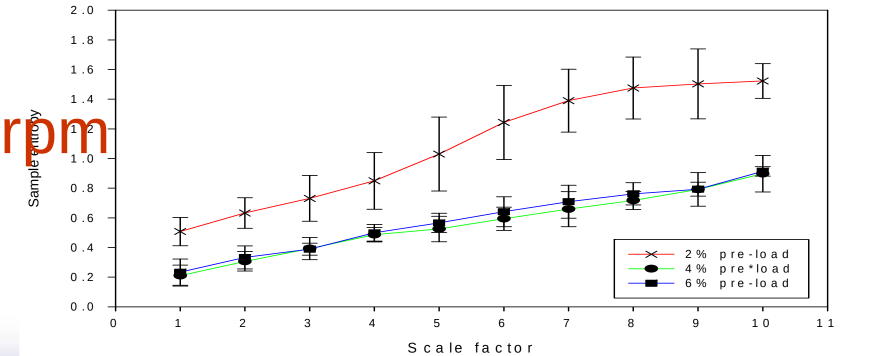


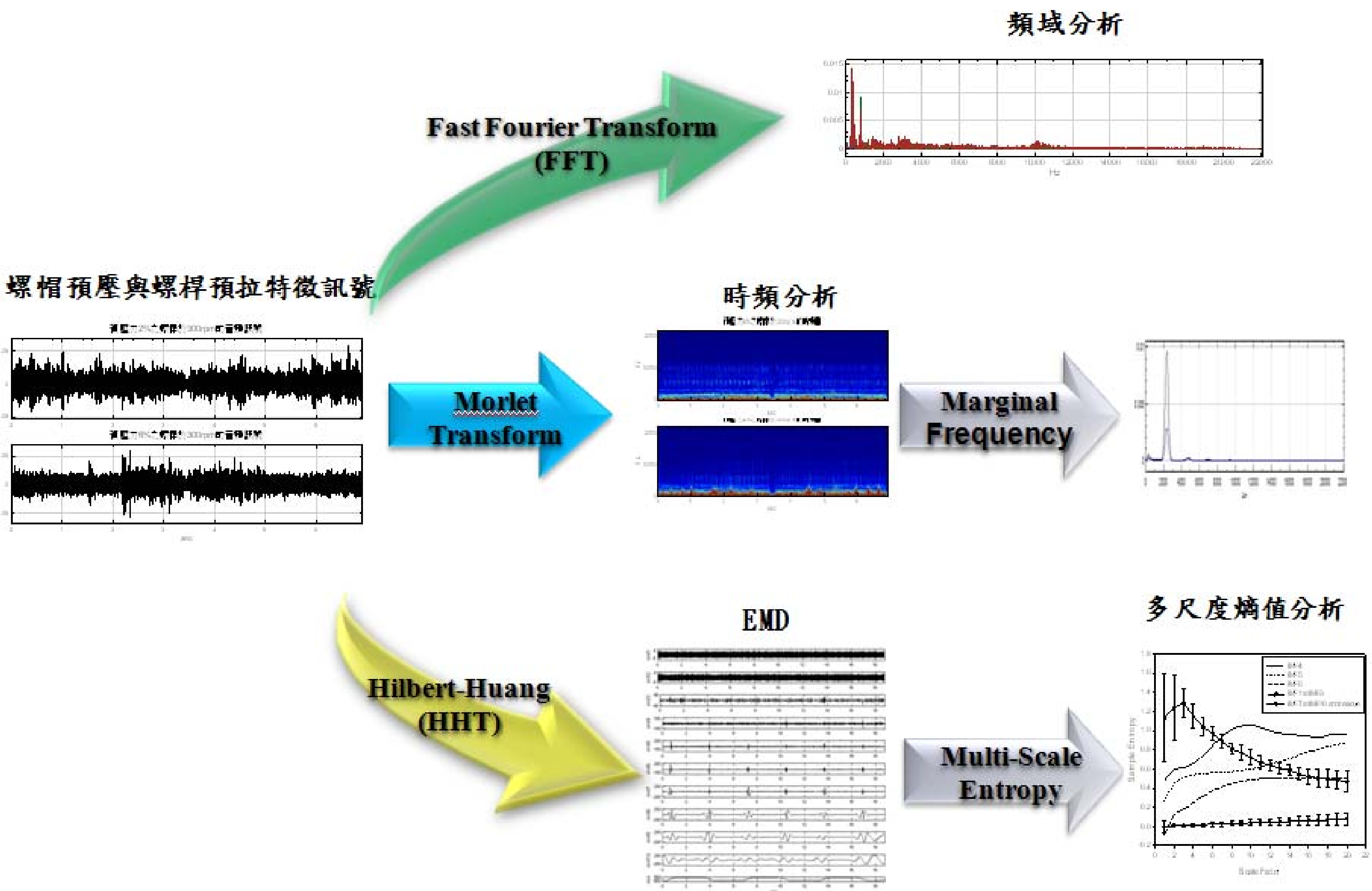
1500rpm





3000rpm




頻域分析
Fast Fourier Transform (FFT)
螺帽預壓與螺桿預拉特徵訊號
時頻分析
Morlet Transform
Marginal Frequency
EMD
Hilbert-Huang (HHT)
Multi-Scale Entropy
多尺度熵值分析

智能化螺帽預壓監測

- 改變不同螺帽預壓量的滾珠導螺桿，透過馬達驅動器，擷取機台往覆運動時馬達的驅動電流訊號，再以經驗模態分析法(EMD)拆解訊號，找出預壓變化的特徵信號，並選擇適當內稟模態函數(IMF)，進行希爾伯特轉換(HHT)，觀測其時頻圖，判定發生預壓失效的時間特徵，最後以多尺度熵(MSE)值來分析滾珠導螺桿預壓失效時訊號複雜度的趨勢。

Concluding Remarks

- To summarize, one can drive the ball screw, perform the current data acquisition, and calculate the comparative evaluations of the proposed method before manufacturing.
- Thus, the machinery status of preload loss or not will be identified and known in advance before operation.

Concluding Remarks

- Experimental results are extremely promising for prognostic monitoring on preload loss in industry.
- Use of this technique for diagnosing a ball screw preload loss through the motor torque current signals is solid and successful.
- Such results comply with the sensorless framework for future manufacturing processes and a module for smart-sensing the health of ball screws is available.

Thank You !