



# 永磁線型同步馬達之驅動與智慧型控制

Drive and Intelligent Control of Permanent  
Magnet Linear Synchronous Motor

國立中央大學電機工程學系講座教授  
林法正

[linfj@ee.ncu.edu.tw](mailto:linfj@ee.ncu.edu.tw)



# 內 容

- 一、緒論
- 二、永磁線型同步結構和工作原理
- 三、永磁線型同步馬達之驅動系統
- 四、擾動觀測器之強健控制系統
- 五、遞迴式類神經網路控制的理論基礎
- 六、利用遞迴式類神經網路之強健控制系統
- 七、利用遞迴式類神經網路之適應混合型控制系統
- 八、遞迴式模糊類神經網路控制的理論基礎
- 九、利用遞迴式模糊類神經網路於積分-比例位置控制器  
線上增益調整之控制系統
- 十、結論與未來的研究發展



# 一、緒論

## □研究動機與目的

〔文〕直接以線型馬達驅動機構具有下列優點：

- 不受齒隙影響及具有較小的摩擦力
- 長距離移動及高精密度
- 簡單的機械結構
- 高推力

〔文〕沒有齒輪或滾珠螺桿等配備，具有下列缺點：

- 易受漣波力的影響
- 易受系統參數變化及外來擾動的影響

〔文〕如何設計控制器去補償這些等效作用力的干擾

# 一、緒論(續)



## 控制架構

### ●擾動抑制控制系統：

- \* 參數變化和外來負載干擾皆被視為一等效干擾訊號
- \* 利用驅動系統的簡單反動態方程式來設計
- \* 利用推力控制器做為內迴路控制器，以前饋控制來增強控制系統之強健性
- \* 若參數變化量或外來干擾量過大或者是變化量的動態太複雜時，不能對伺服驅動系統提供足夠的強健性

# 一、緒論(續)

## ●類神經網路

- \* 在控制系統上處理非線性項及未確定項
- \* 架構分成前饋式及遞迴式類神經網路
- \* 前饋式類神經網路是靜態映射，加上延遲連接可處理動態部份，但需要大量神經元且對訓練之資料較為靈敏
- \* 遞迴式類神經網路具有內部反饋迴路，是動態映射結構，對系統未知模式、參數變化及外力擾動具有良好控制成效

# 一、緒論(續)

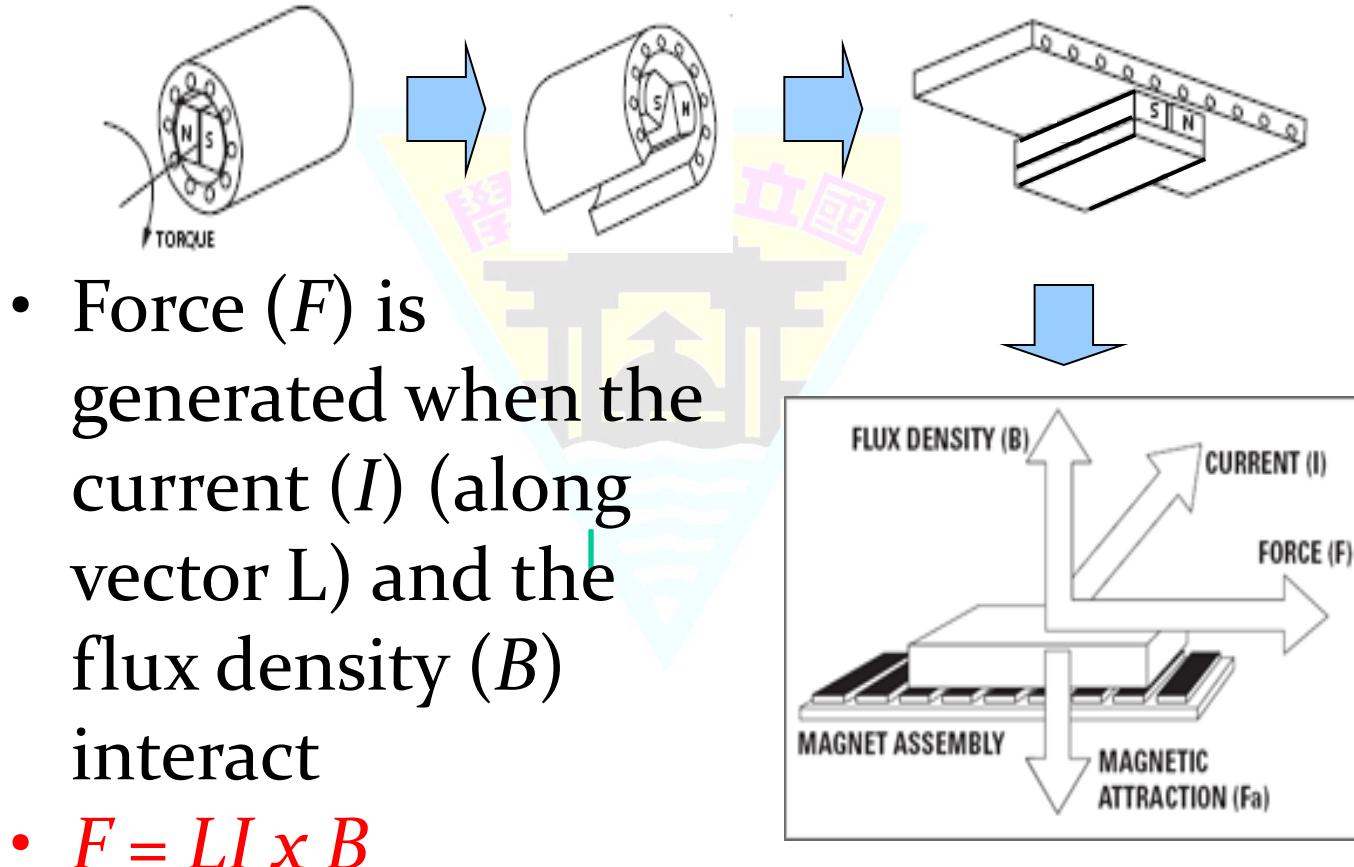
## ■ 控制器之設計：

- 遲迴式類神經網路補償器
- 遲迴式類神經網路控制器
- 遲迴式類神經網路之混合型與適應混合型控制系統
- 遲迴式模糊類神經網路於積分-比例位置控制器線上增益調整之控制系統



# Basics of Linear Motors

- Analogous to Unrolled Permanent Magnet Synchronous Motor



# Linear Motors in Action



- [http://www.parkermotion.com/video/Braas\\_Triology\\_T3E\\_Video.MPG](http://www.parkermotion.com/video/Braas_Triology_T3E_Video.MPG)

# Analysis of Linear Motors

- **Analysis is similar to that of rotary machines**
  - Linear dimension and displacements replace angular ones
  - Forces replace torques
  - Commutation cycle is distance between two consecutive pole pairs instead of 360 degrees



# Benefits of Linear Motors

- High Maximum Speed
  - Limited primarily by bus voltage, control electronics
- High Precision
  - Accuracy, resolution, repeatability limited by feedback device, budget
  - Zero backlash: No mechanical transmission components.
- Fast Response
  - Response rate can be over 100 times that of a mechanical transmission → faster accelerations, settling time (more throughput)
- Stiffness
  - No mechanical linkage, stiffness depends mostly on gain & current
- Durable
  - Modern linear motors have few/no contacting parts → no wear

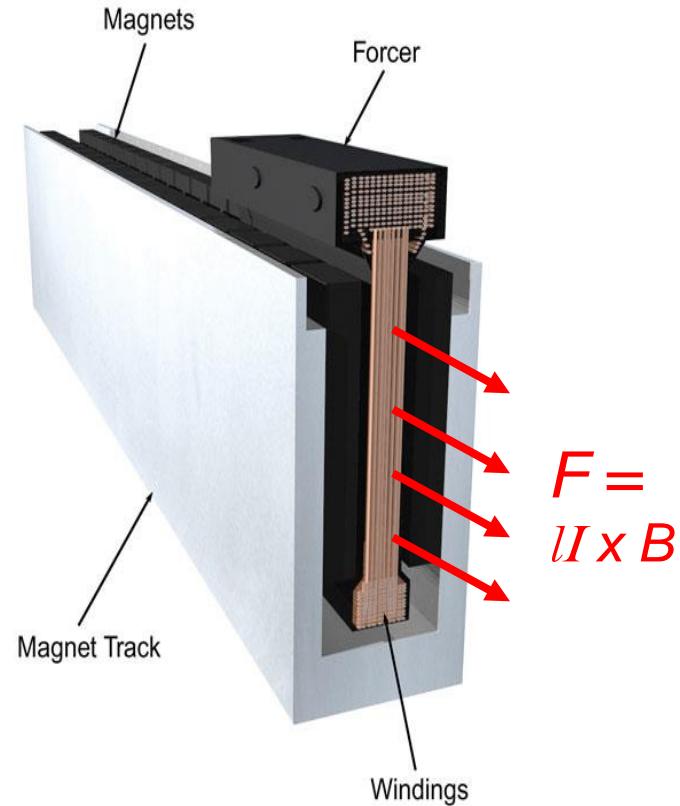
# Downsides of Linear Motors

- Cost
  - Low production volume (relative to demand)
  - High price of magnets
  - Linear encoders (feedback) are much more expensive than rotary encoders, cost increases with length
- Higher Bandwidth Drives and Controls
- Lower force per package size
- Heating issues
  - Forcer is usually attached to load →  $I^2R$  losses are directly coupled to load
- No (minimal) Friction
  - No automatic brake



# Components of Linear Motors

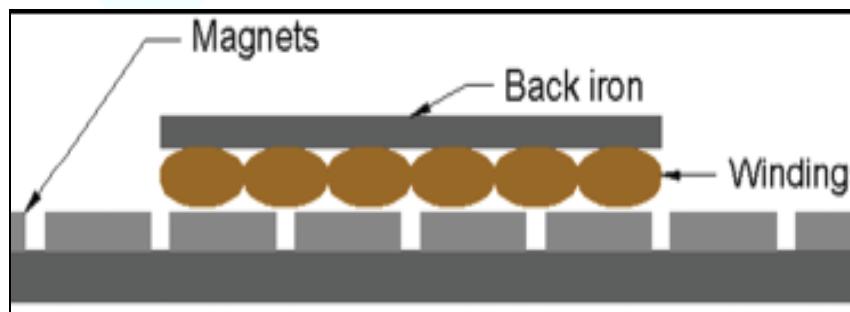
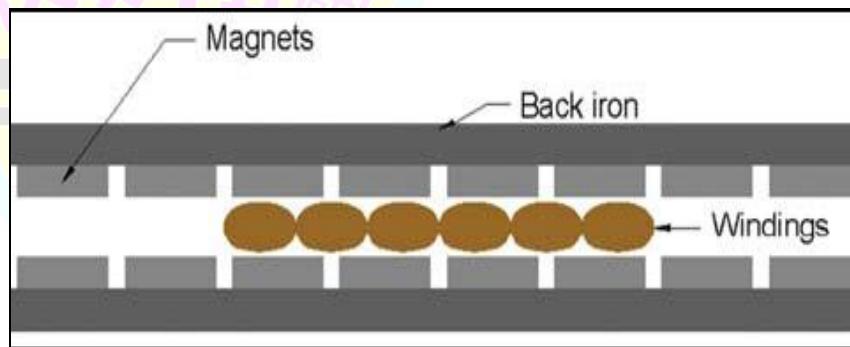
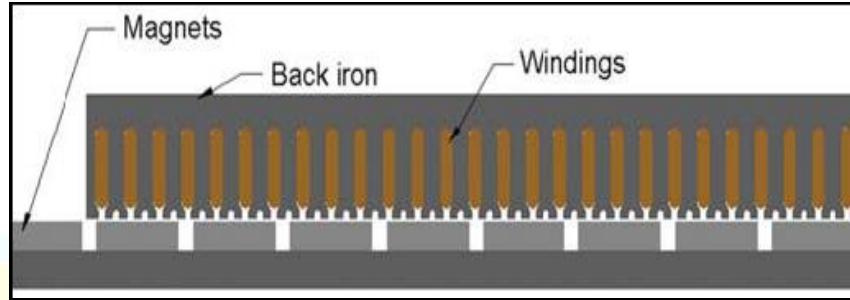
- **Forcer (Motor Coil)**
  - Windings (coils) provide current (I)
  - Windings are encapsulated within core material
  - Mounting Plate on top
  - Usually contains sensors (hall effect and thermal)
- **Magnet Rail**
  - Iron Plate / Base Plate
  - Rare Earth Magnets of alternating polarity provide flux (B)
  - Single or double rail





# Types of Linear Motors

- Iron Core
  - Coils wound around teeth of laminations on forcer
- Ironless Core
  - Dual back iron separated by spacer
  - Coils held together with epoxy
- Slotless
  - Coil and back iron held together with epoxy





# Linear Motor Types: Iron Core

## Distinguishing Feature

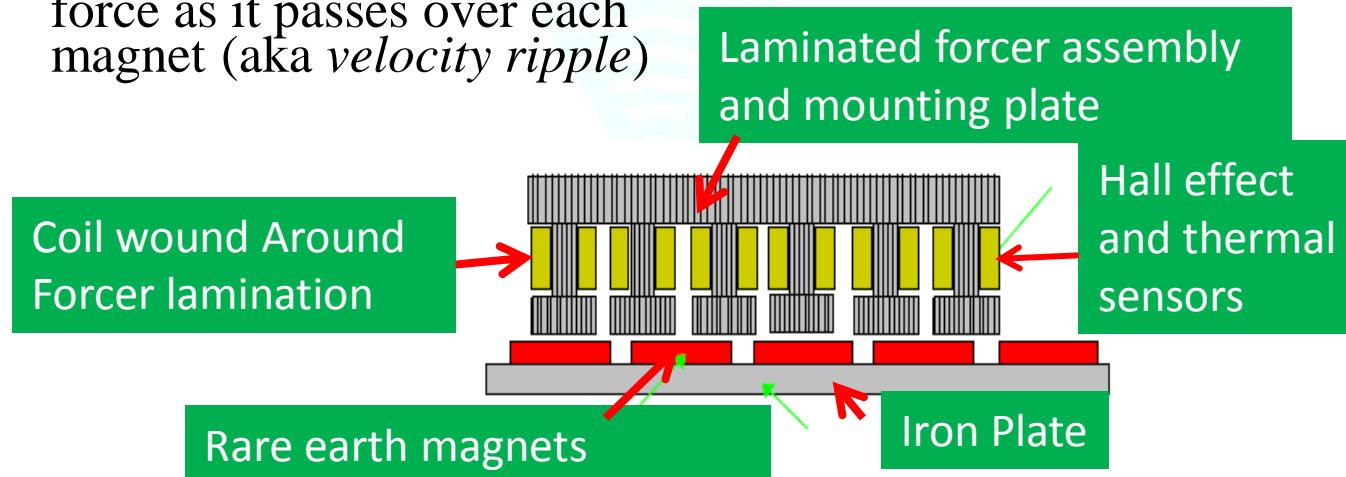
- Copper windings around forcer laminations over a single magnet rail

## Advantages:

- Highest force available per unit volume
- Efficient Cooling
- Lower cost

## Disadvantages:

- High attractive force between forcer & magnet track
- Cogging: iron forcer affects thrust force as it passes over each magnet (aka *velocity ripple*)



# Linear Motor Types: Ironless



## Distinguishing Feature

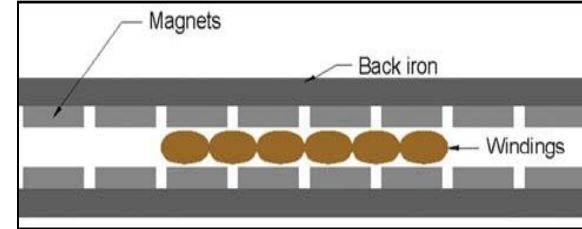
- Forcer constructed of wound coils held together with epoxy and running between two rails (North and South)
- Also known as “Aircore” or “U-channel” motors

## Advantages:

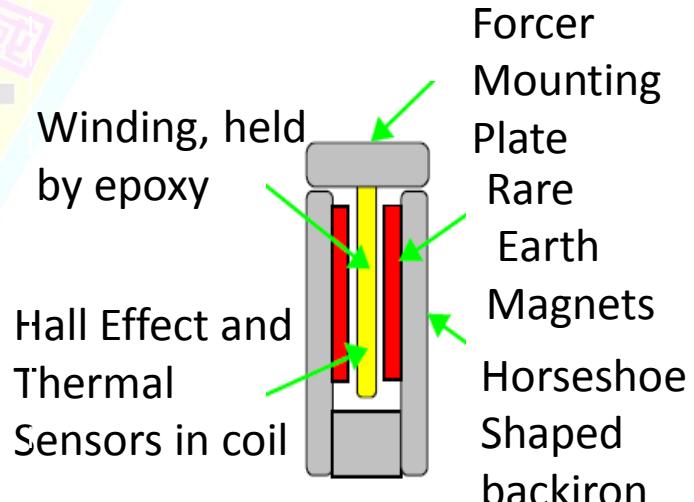
- No attractive forces in forcer
- No Cogging
- Low weight forcer - No iron means higher accel/decel rates

## Disadvantages:

- Low force per package size
- Lower Stiffness; limited max load without improved structure
- Poor heat dissipation
- Higher cost (2x Magnets!)



## Front View





# Linear Motor Types: Slotless

## Distinguishing Feature

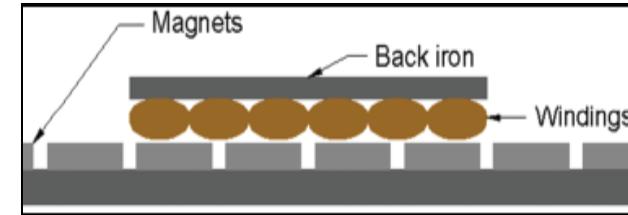
- Mix of ironless and iron core:  
coils with back iron contained  
within aluminum housing over a  
single magnet rail

## Advantages over ironless:

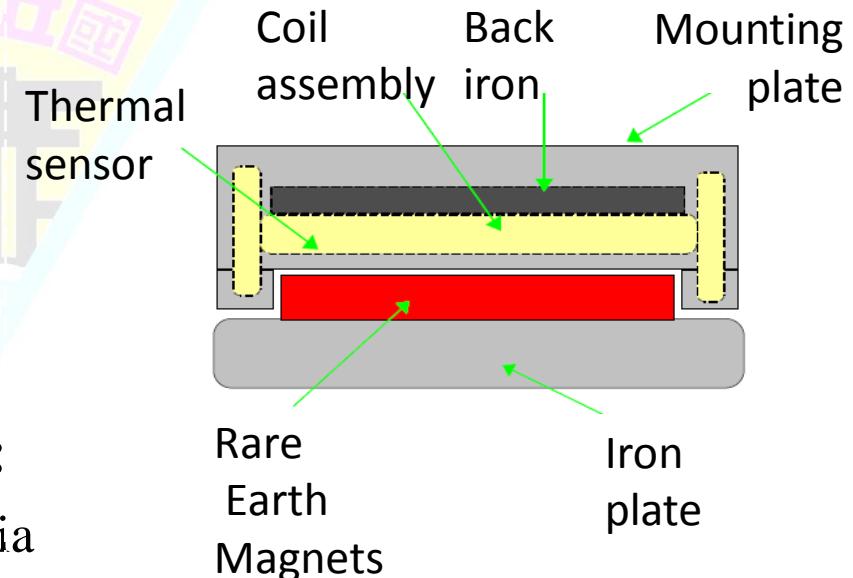
- Lower cost (1x magnets)
- Better heat dissipation
- Structurally stronger forcer
- More force per package size

## Advantages over iron core:

- Lighter weight and lower inertia  
forcer
- Lower attractive forces
- Less cogging



Front View

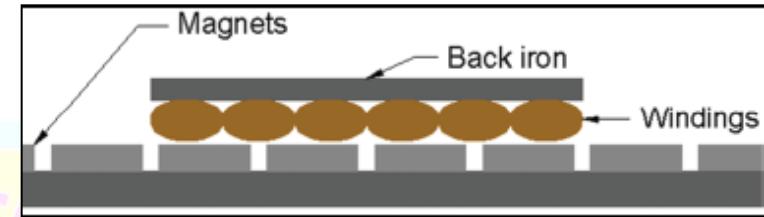




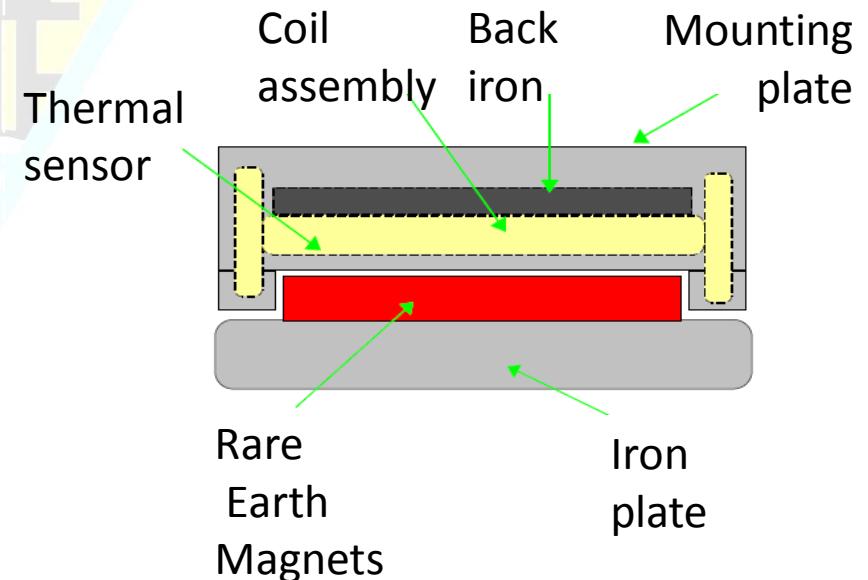
# Linear Motor Types: Slotless

## Disadvantages

- Some attractive force and cogging
- Less efficient than iron core and ironless - more heat to do the same job



Front View





# Linear Motor Type Comparison

	Linear Brushless DC Motor Type		
Feature	Iron Core	Ironless	Slotless
<b>Attraction Force</b>	Most	None	Moderate
<b>Cost</b>	Medium	High	Lowest
<b>Force Cogging</b>	Highest	None	Medium
<b>Power Density</b>	Highest	Medium	Medium
<b>Forcer Weight</b>	Heaviest	Lightest	Moderate



# Components of a “Complete” Linear Motor System

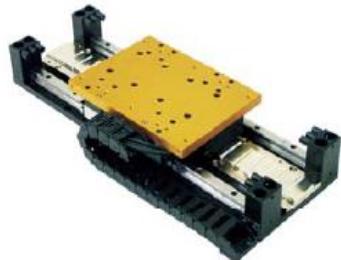
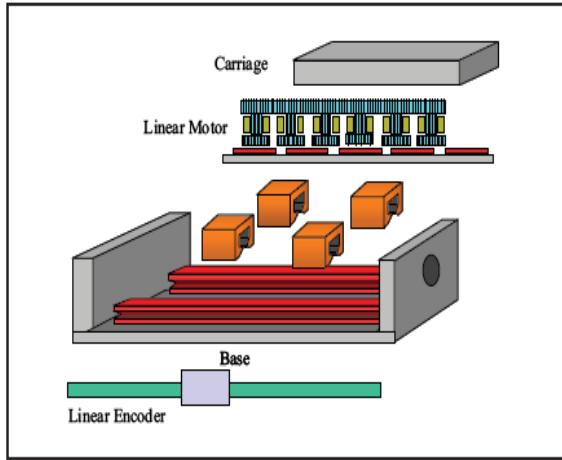
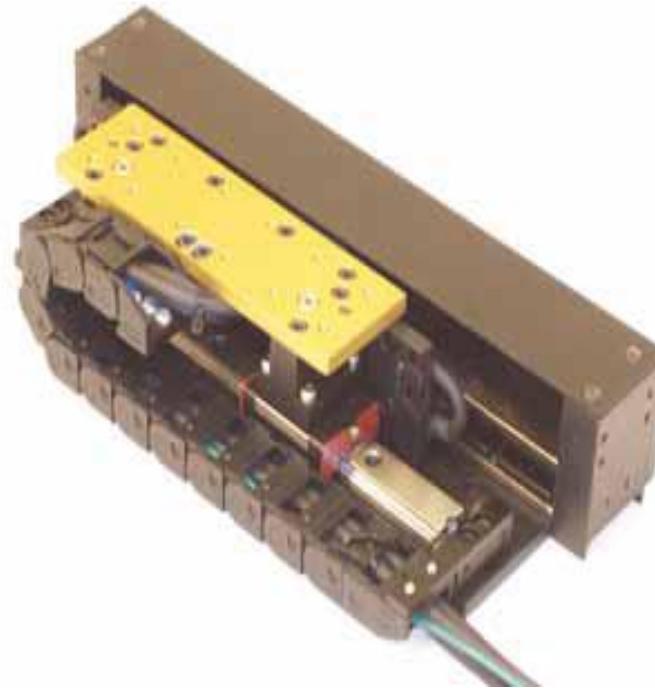


Fig. 7: Parker Trilogy's TR Series Ironcore Linear Motor Positioner

1. Motor components
2. Base/Bearings
3. Servo  
controller/feedback  
elements
  - Typical sensors include Hall Effect (for position) and thermal sensors
4. Cable management

# Sample Pricing

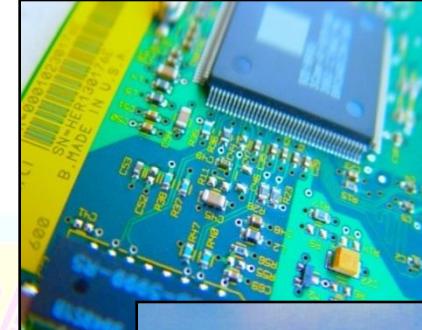
- \$3529
- Trilogy T1S Ironless linear motor
- 110V, 1 pole motor
- Single bearing rail
- ~12" travel
- magnetic encoder
- Peak Velocity = 7 m/s
- Resolution = 5μm





# Applications

- **Small Linear Motors**
  - Packaging and Material Handling
  - Automated Assembly
  - Reciprocating compressors and alternators
- **Large Linear Induction Machines (3 phase)**
  - Transportation
  - Materials handling
  - Extrusion presses





## 二、永磁線型同步馬達的結構和工作原理

### ■ 永磁線型同步馬達

- 美國TRILOGY公司所製造，其型號為LM310-1
- 一次側為動子，內含三相繞組，是由一短的移動”一次側”線圈，包含螺旋狀之電樞線圈與霍爾感測器所組成
- 一長的固定”二次側”線圈，包含由釤鐵硼所組成的永磁和線型滑軌與線型尺規所組成
- 驅動器為一般控制永磁同步馬達之磁場導向電流控制的脈寬調變電壓源三相反流器
- 規格為110伏特、2.9安培、46瓦特、57.8牛頓  
永磁極距為6.096公分



## 二、永磁線型同步馬達的結構和工作原理(續)

### ● 馬達外觀圖

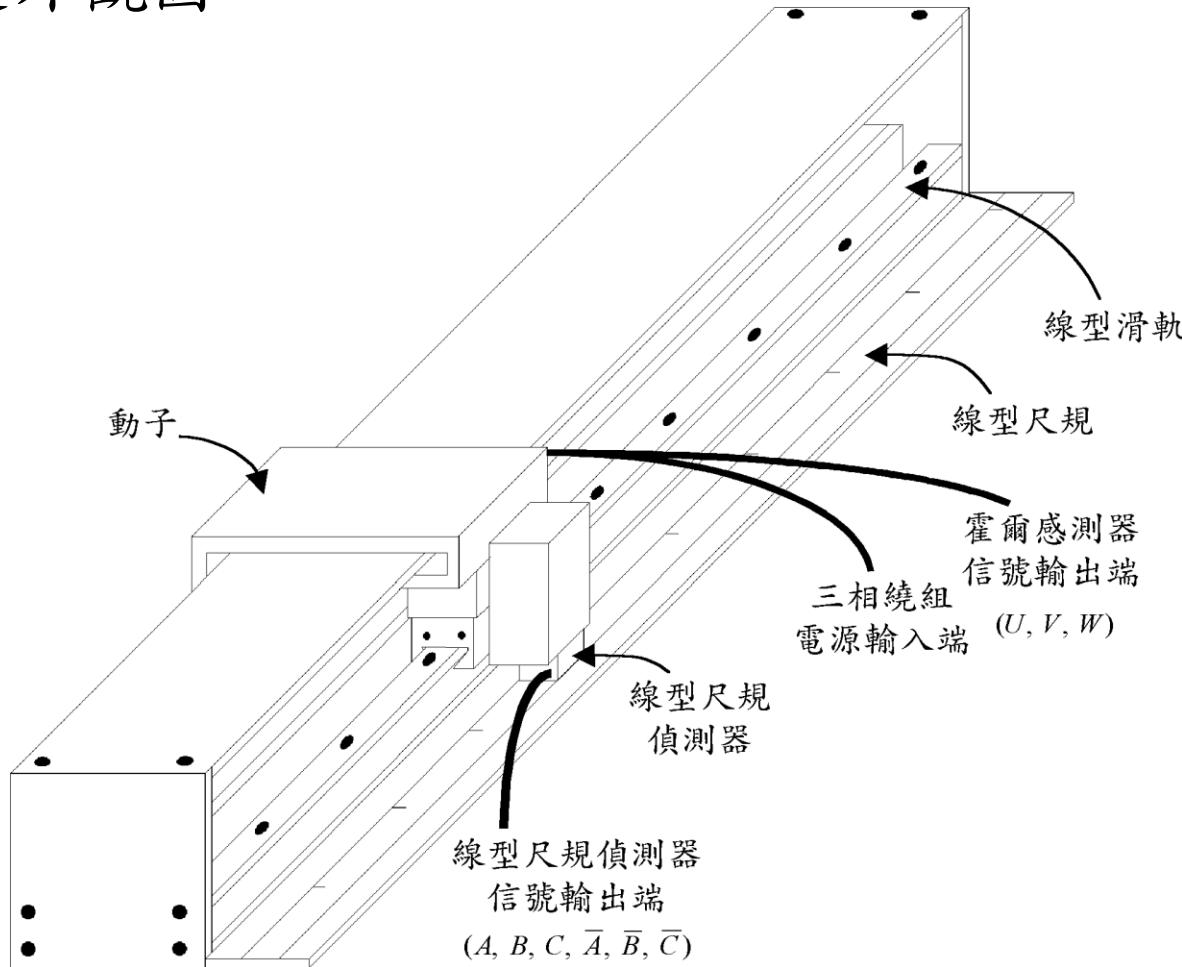


圖 2.1



## 二、永磁線型同步馬達的結構和工作原理(續)

### □工作原理

#### 電壓方程式

- 三相二極永磁線型同步馬達的相電壓方程式

$$\mathbf{v}_{abc} = \mathbf{r}_s \dot{\mathbf{i}}_{abc} + p\lambda_{abc} \quad (2.1)$$

- 利用同步參考座標轉換後之d-q 軸的電壓方程式

$$v_q = r_s i_q + p\lambda_q + \omega \lambda_d \quad (2.8)$$

$$v_d = r_s i_d + p\lambda_d - \omega \lambda_q \quad (2.9)$$

## 二、永磁線型同步馬達的結構和工作原理(續)



### 作用力方程式

- $P$  極對的永磁線型同步馬達的推力方程式

$$F_e = \frac{3\pi P}{2\tau} [i_q \lambda_m + (L_d - L_q) i_d i_q] \quad (2.25)$$

$$F_e = \frac{3\pi P}{2\tau} i_q \lambda_m \quad (2.26)$$

- 永磁線型同步馬達動子的動態方程式

$$F_e = Mp v + Dv + w \quad (2.27)$$

## 二、永磁線型同步馬達的結構和工作原理(續)



### □ 磁場導向控制之馬達驅動系統之架構圖

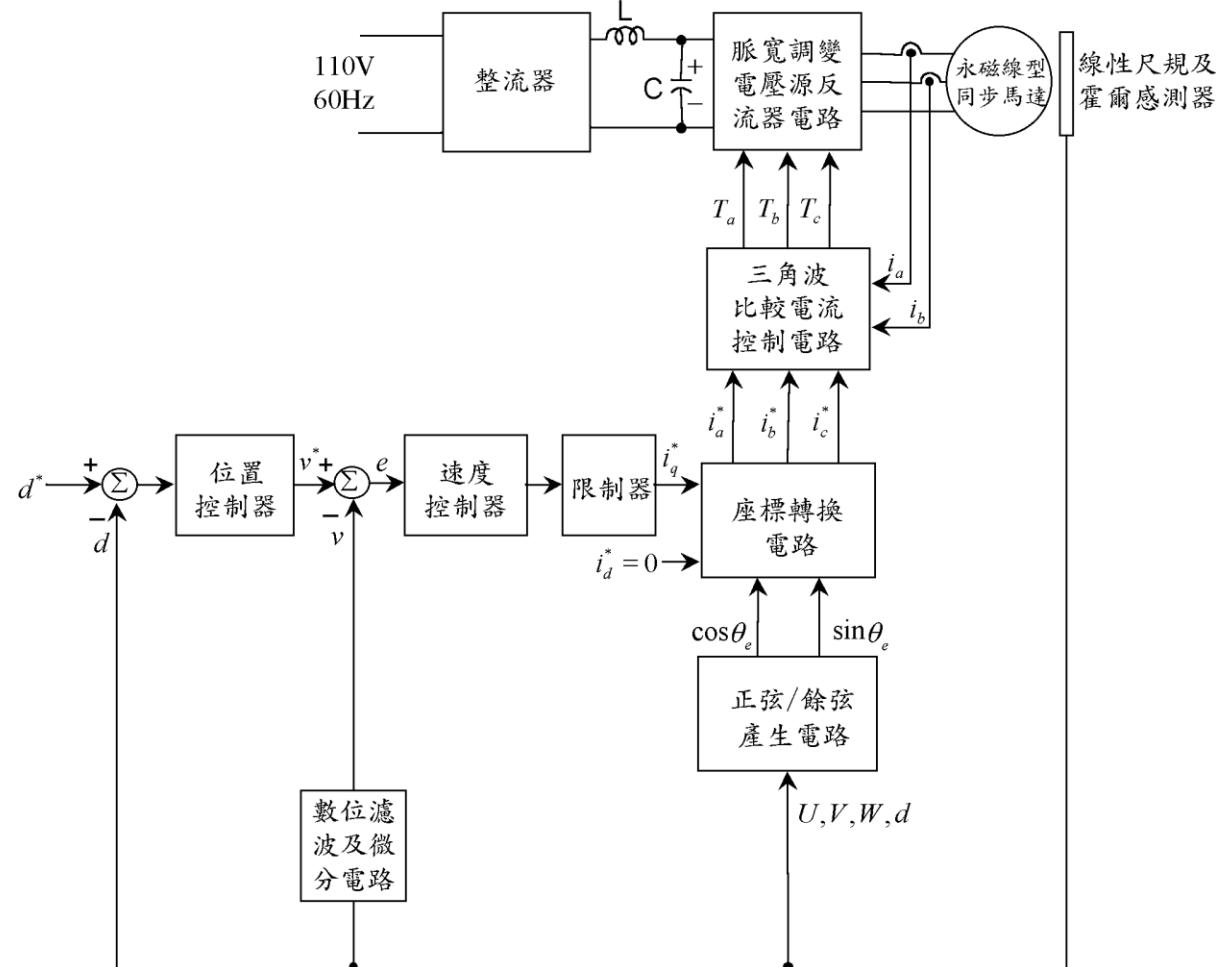


圖 2.9

## 二、永磁線型同步馬達的結構和工作原理(續)



### □ 簡化之馬達驅動系統方塊圖

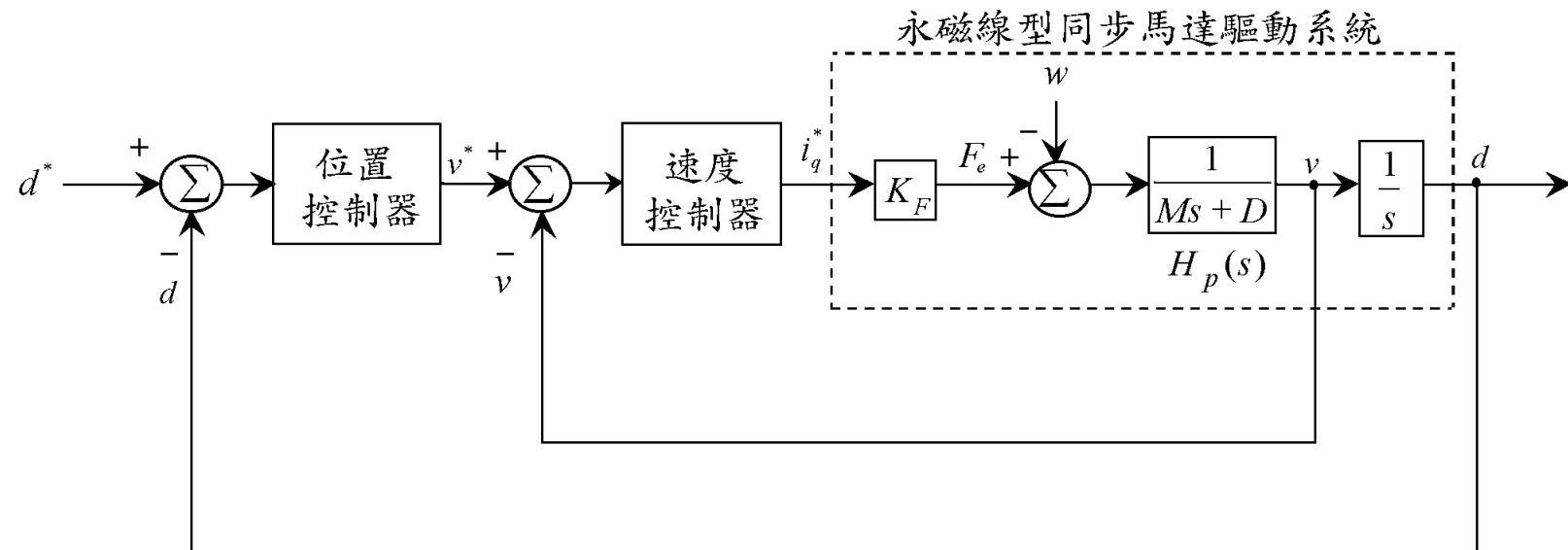


圖 2.10



## 三、永磁線型同步馬達之驅動系統

### 馬達驅動系統電路

- 電流感測電路
- 保護電路
- 三角波比較之電流控制電路
- 互鎖電路(Lockout Circuit)
- 隔離電路
- 智慧型功率模組(Intelligent Power Module, IPM)
- 其他相關電路

### 三、永磁線型同步馬達之驅動系統(續)

#### 馬達驅動系統方塊圖

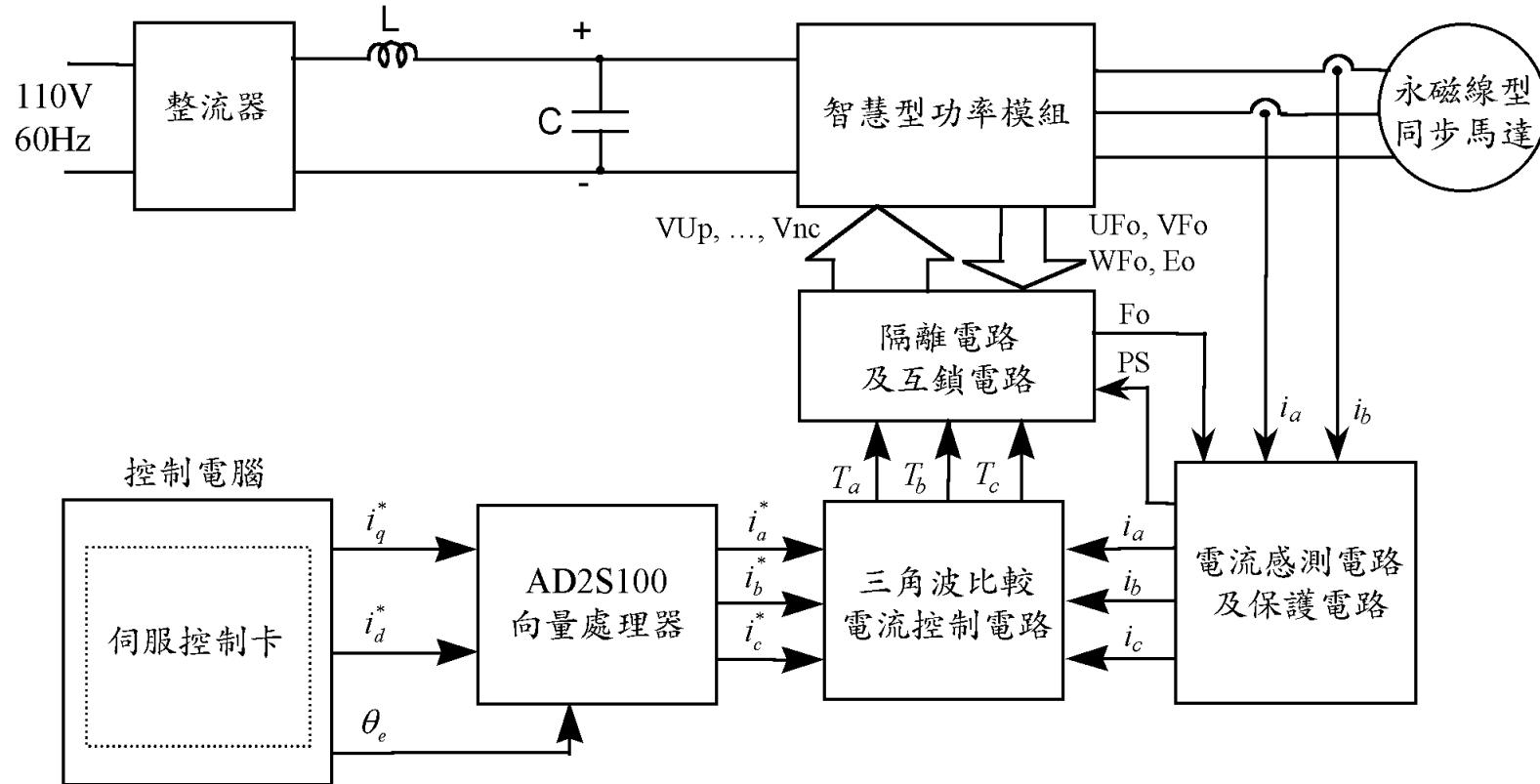


圖 3.1

### 三、永磁線型同步馬達之驅動系統(續)

#### 電腦控制之永磁同步馬達驅動系統

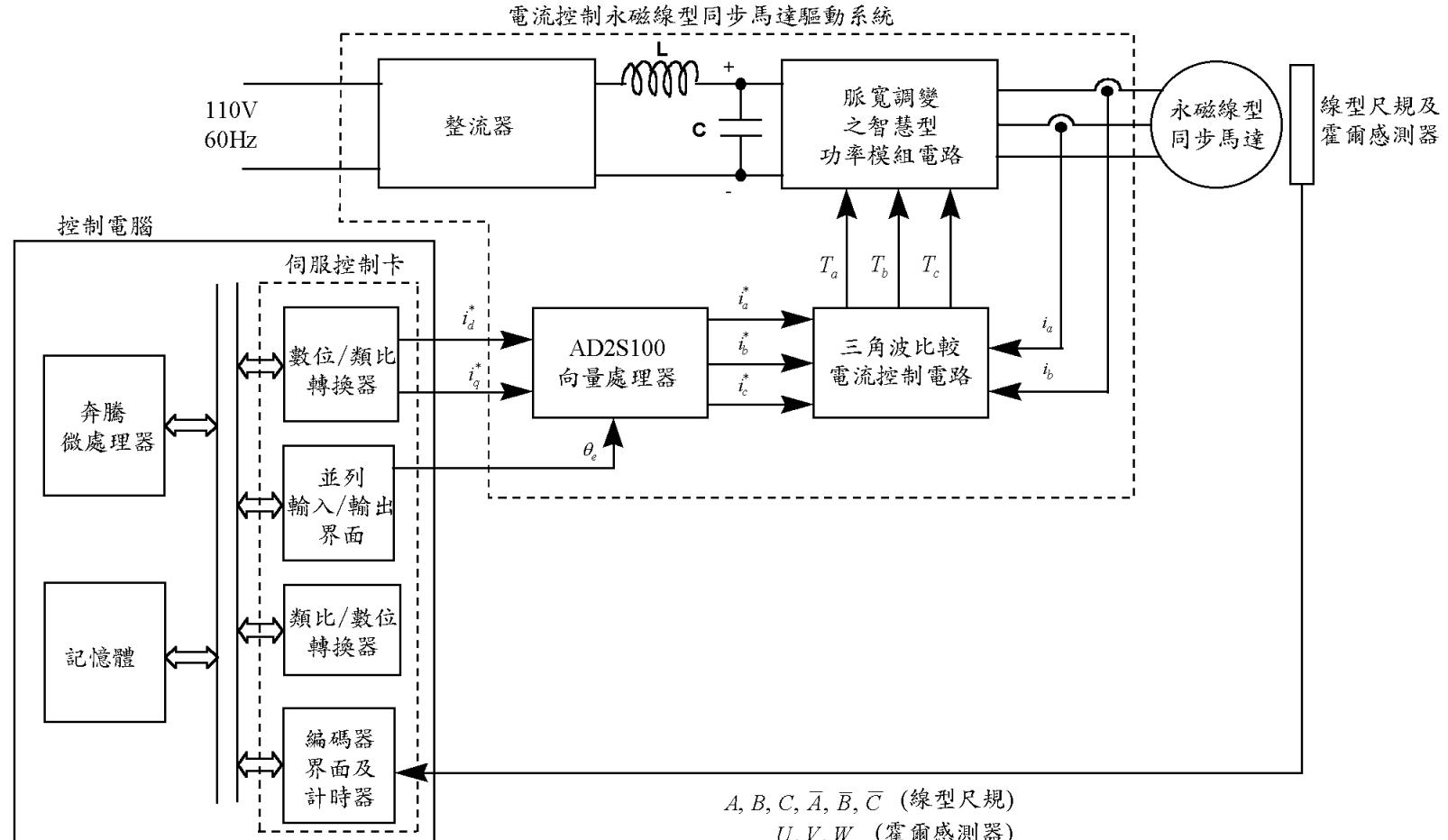


圖 3.9

### 三、永磁線型同步馬達之驅動系統(續)

□ 驅動系統  
軟體程式  
流程圖

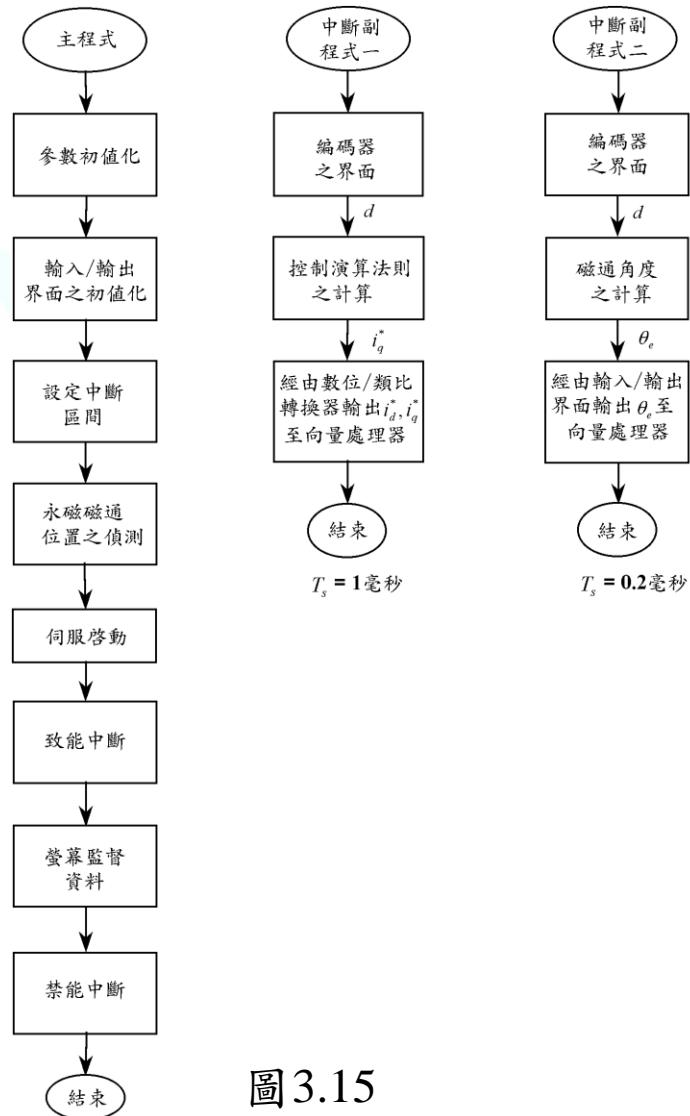


圖 3.15



## 四、擾動觀測器之強健控制系統

### □ 積分-比例位置控制器

適用狀況：一般標準模式無參數變化和外來負載干擾  
之步階命令追隨

設計方法：利用動子位置響應對輸入命令之轉移函數

$$\begin{aligned} \left. \frac{d(s)}{d^*(s)} \right|_{w(s)=0} &= \frac{K_s K_I K_F b}{s^3 + (a + K_p K_F b)s^2 + K_I K_F b s + K_s K_I K_F b} \\ &\triangleq \frac{h_1}{s + \mu_1} + \frac{h_2}{s + \mu_2} + \frac{h_3}{s + \mu_3} \end{aligned} \quad (4.1)$$

$$K_p = (\mu_1 + \mu_2 + \mu_3 - a) / (K_F b) \quad (4.2)$$

$$K_I = (\mu_1 \mu_2 + \mu_2 \mu_3 + \mu_1 \mu_3) / (K_F b) \quad (4.3)$$

$$K_s = (\mu_1 \mu_2 \mu_3) / (K_I K_F b) \quad (4.4)$$

# 四、擾動觀測器之強健控制系統(續)

## 積分-比例位置控制方塊圖

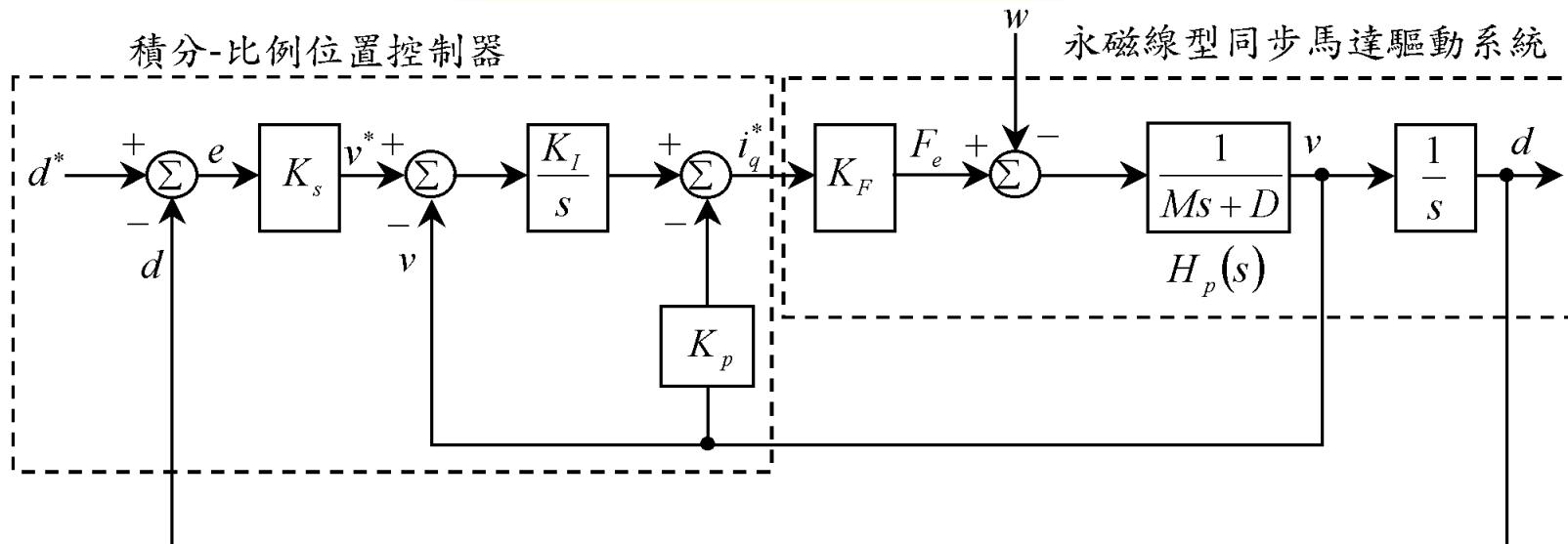


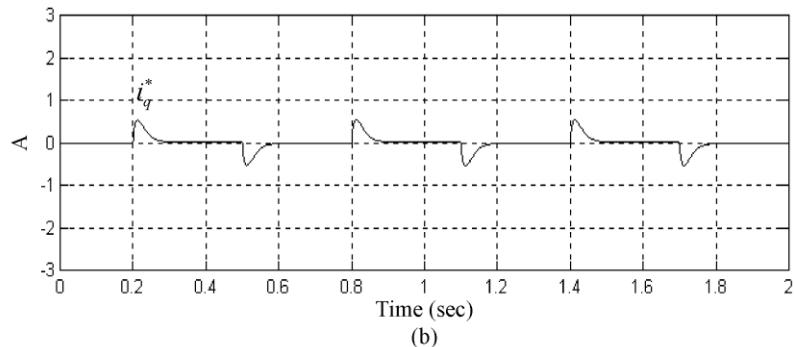
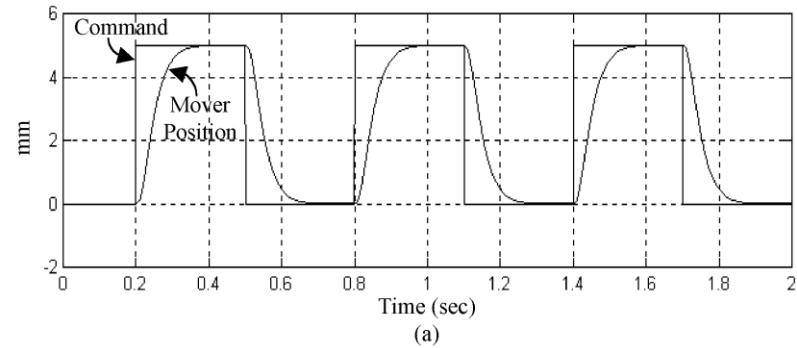
圖 4.1

# 四、擾動觀測器之強健控制系統(續)

## □ 模擬結果

### 積分-比例位置控制器

標準動子質量



4 倍動子質量

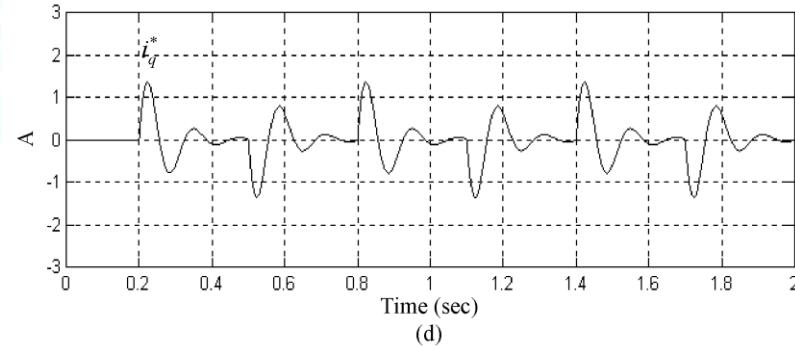
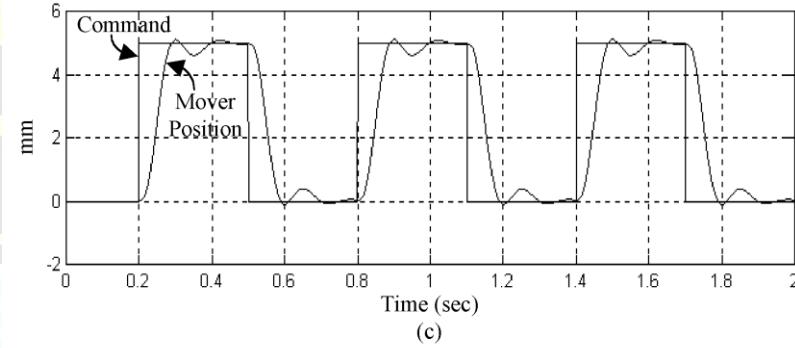


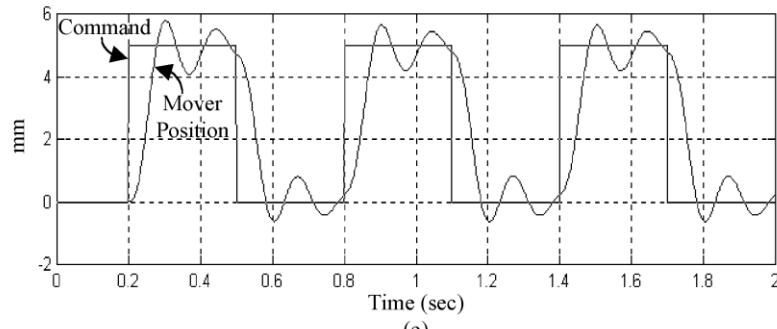
圖 4.3

## 四、擾動觀測器之強健控制系統(續)

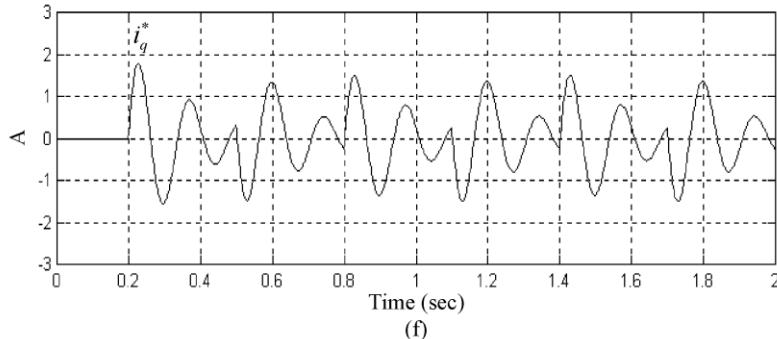
### □ 模擬結果(續)

#### 積分-比例位置控制器

6 倍動子質量

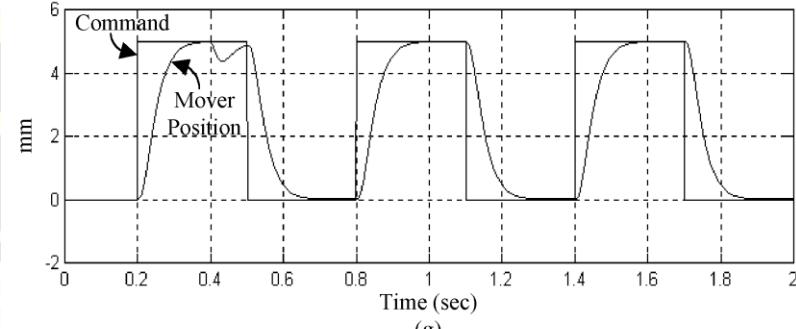


(e)

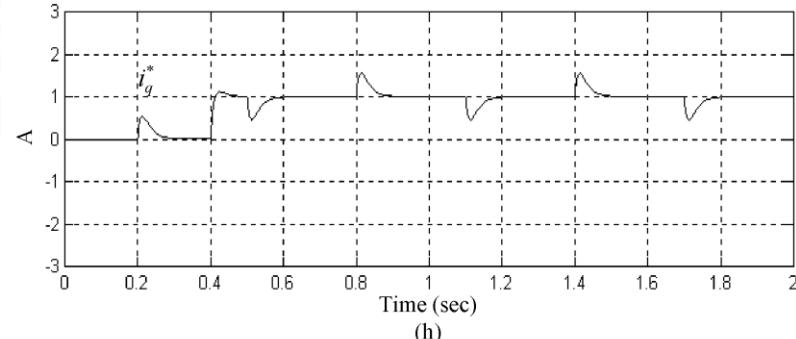


(f)

0.4 秒加負載



(g)



(h)

圖 4.3(續)

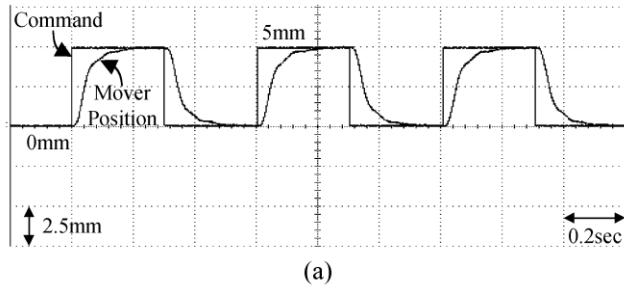


# 四、擾動觀測器之強健控制系統(續)

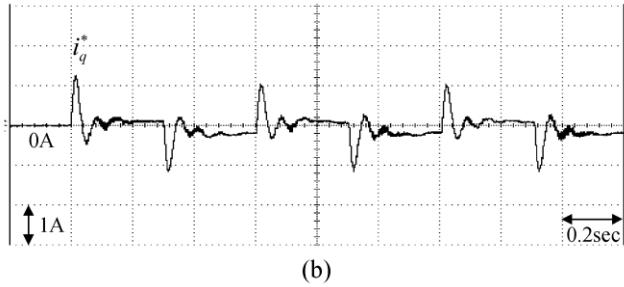
## □ 實測結果

### ■ 積分-比例位置控制器

標準動子質量

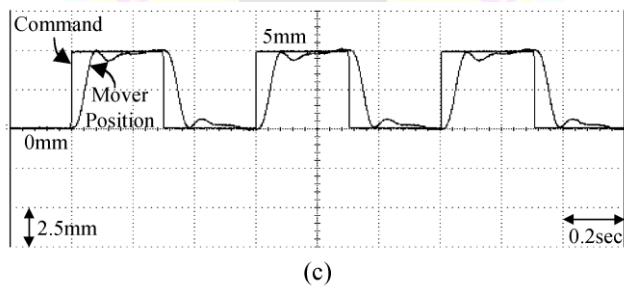


(a)

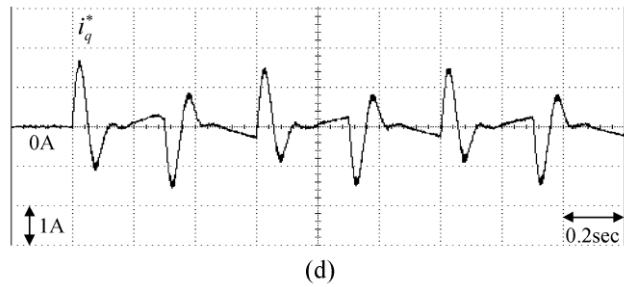


(b)

4 倍動子質量

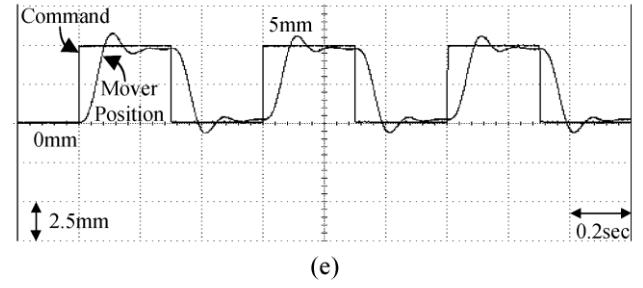


(c)

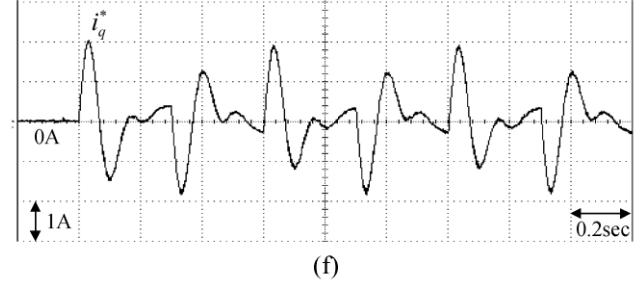


(d)

6 倍動子質量



(e)



(f)

圖 4.4



## □ 擾動觀測器

適用狀況：改善積分-比例位置控制器在未確定項發生時，保持系統所要求的追隨響應規格

設計方法：利用標準模式下驅動系統的反動態方程式，將干擾訊號經由一低通濾波器前饋給積分-比例位置控制器



# 四、擾動觀測器之強健控制系統(續)

## ■ 擾動觀測器控制方塊圖

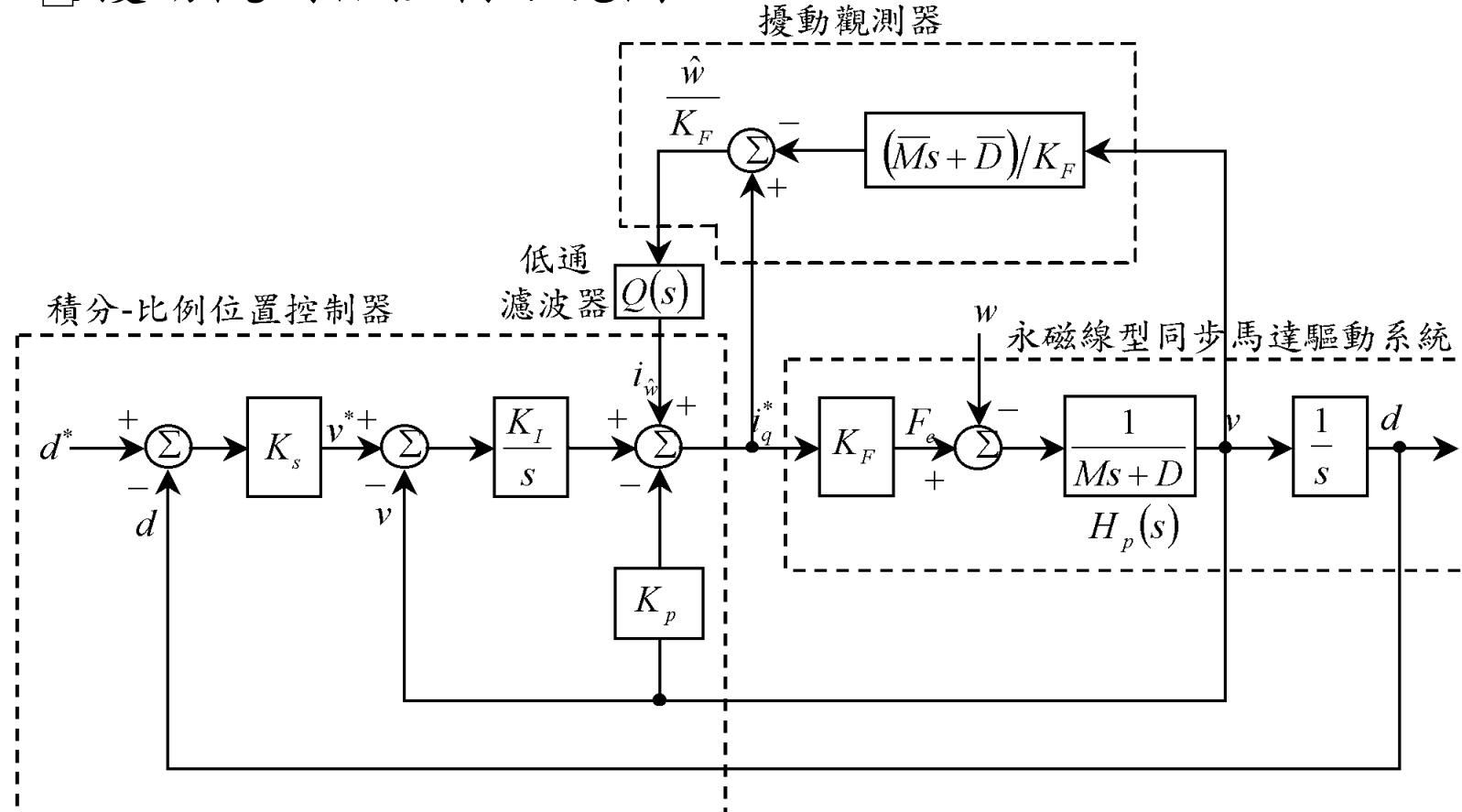


圖 4.2

# 四、擾動觀測器之強健控制系統(續)

## □ 模擬結果

### ■ 擾動觀測器

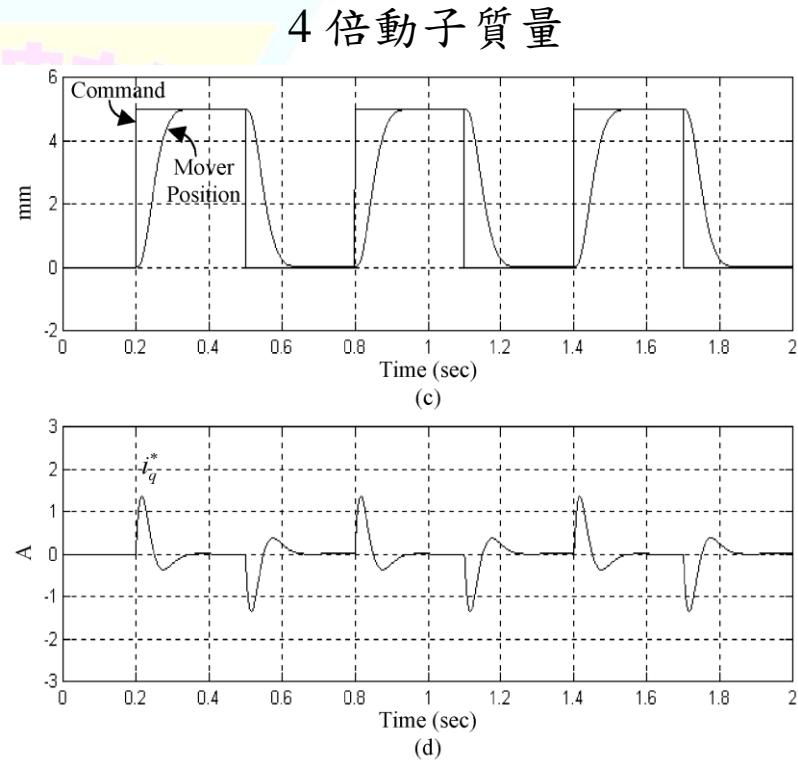
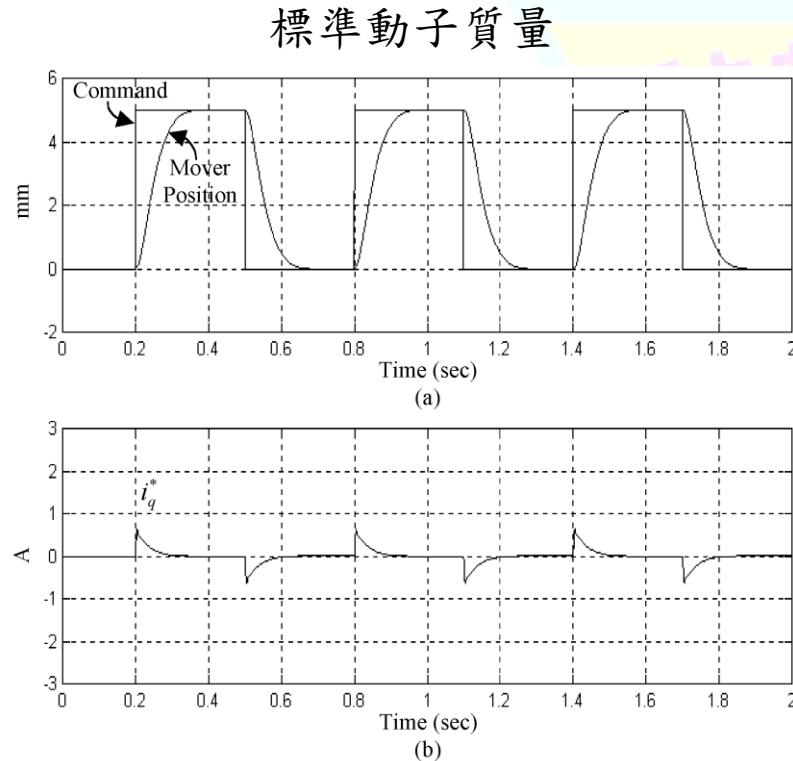


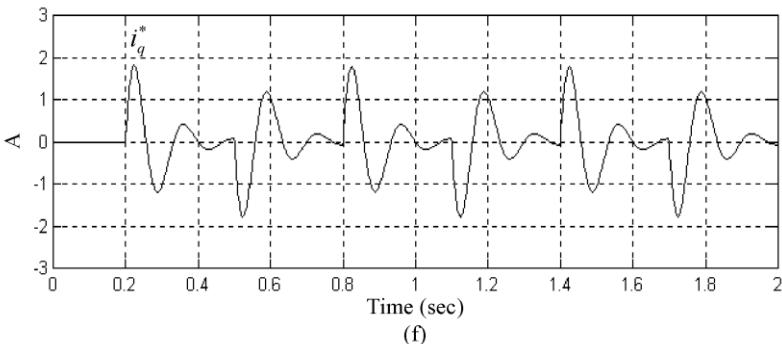
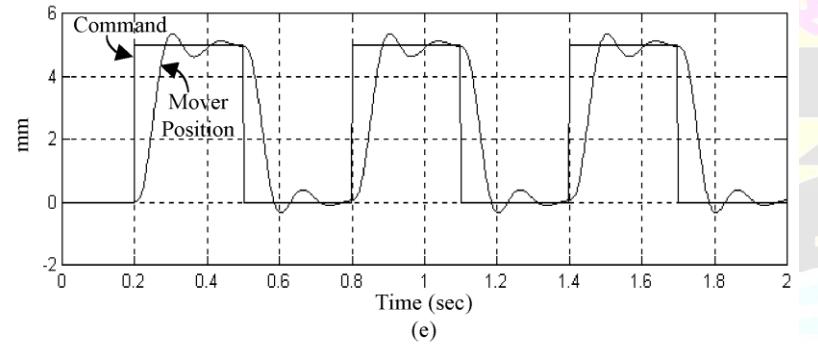
圖 4.5

## 四、擾動觀測器之強健控制系統(續)

### □ 模擬結果(續)

#### ■ 擾動觀測器

6 倍動子質量



0.4 秒加負載

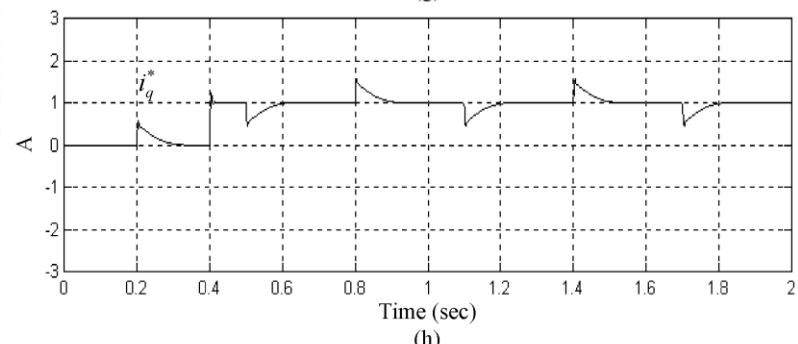
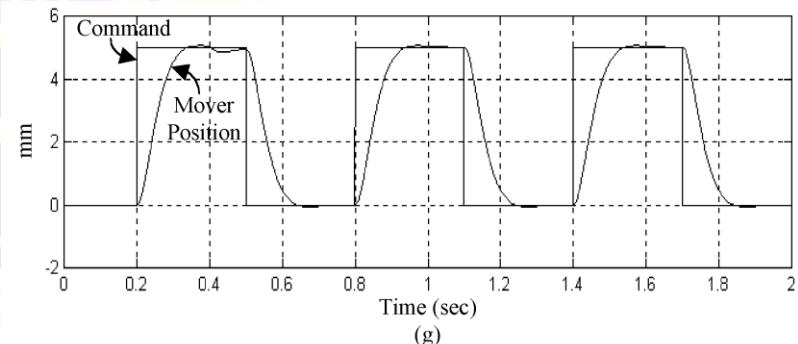


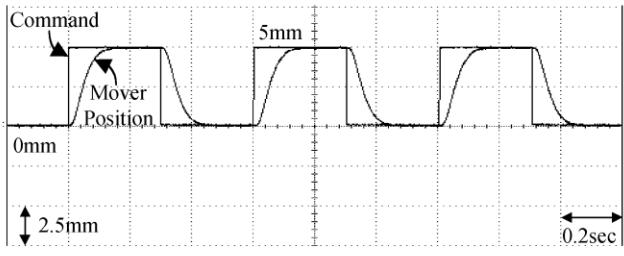
圖 4.5(續)

# 四、擾動觀測器之強健控制系統(續)

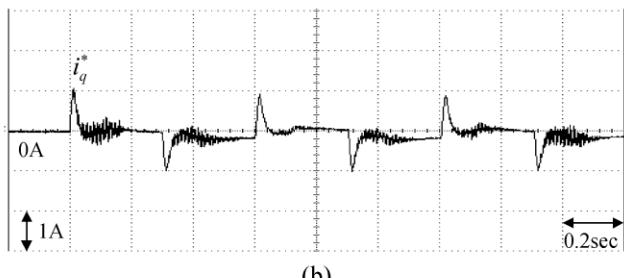
## □ 實測結果

### ■ 擾動觀測器

標準動子質量

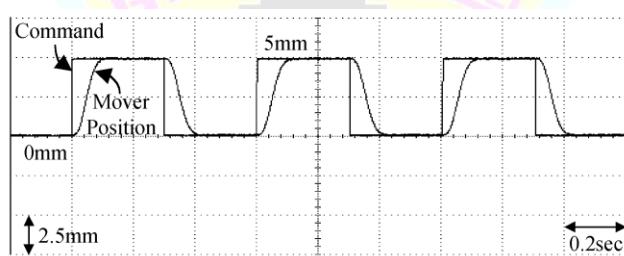


(a)

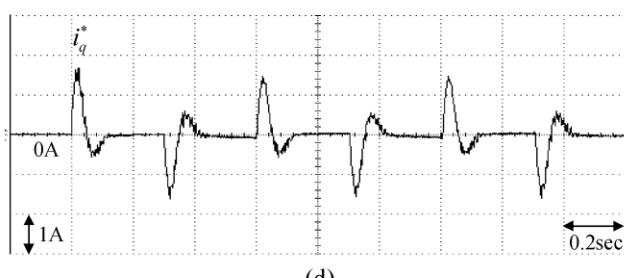


(b)

4倍動子質量

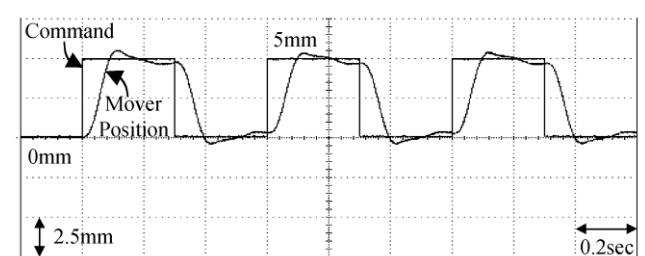


(c)

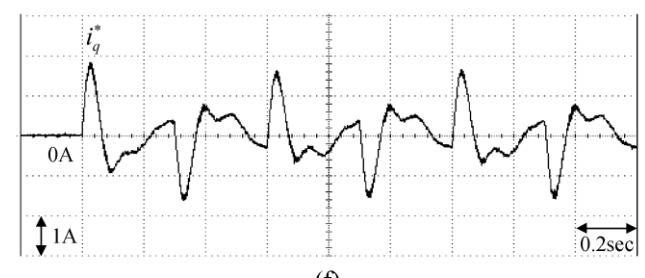


(d)

6倍動子質量



(e)



(f)

圖 4.6



# 五、遞迴式類神經網路控制的理論基礎

## □ 網路架構圖

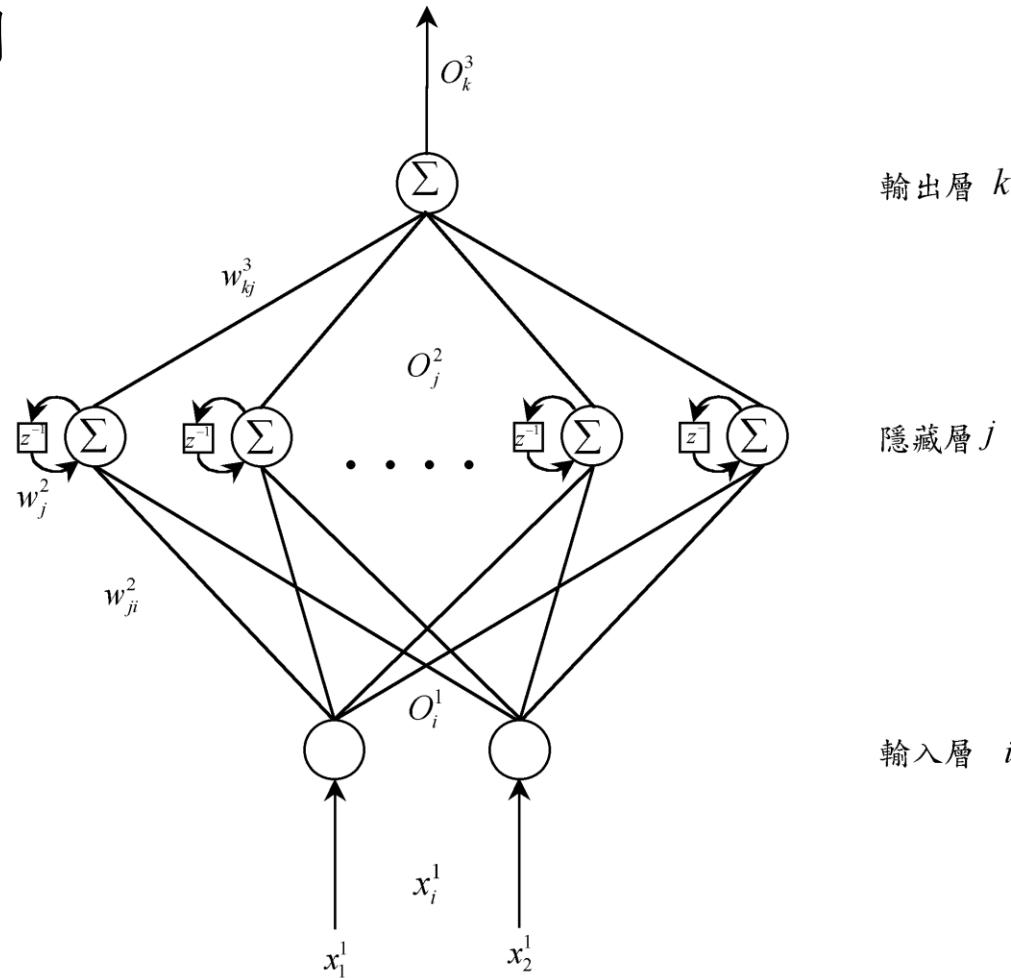


圖 5.1

# 五、遞迴式類神經網路控制的理論基礎(續)



## □ 網路描述

### ■ 輸入層

$$\begin{aligned} net_i^1(N) &= x_i^1(N) \\ O_i^1(N) &= f_i^1(net_i^1(N)) = \frac{1}{1 + e^{-net_i^1(N)}}, \quad i = 1, 2 \end{aligned} \tag{5.1}$$

### ■ 隱藏層

$$\begin{aligned} net_j^2(N) &= w_j^2 O_j^2(N-1) + \sum_i w_{ji}^2 O_i^1(N) \\ O_j^2(N) &= f_j^2(net_j^2(N)) = \frac{1}{1 + e^{-net_j^2(N)}}, \quad j = 1, 2, \dots, R_j \end{aligned} \tag{5.2}$$

### ■ 輸出層

$$\begin{aligned} net_k^3(N) &= \sum_j w_{kj}^3 O_j^2(N) \\ O_k^3(N) &= f_k^3(net_k^3(N)) = net_k^3, \quad k = 1 \end{aligned} \tag{5.3}$$

# 五、遞迴式類神經網路控制的理論基礎(續)



## □ 線上學習法則

### ■ 權重值更新值

$$\Delta w_{kj}^3 = -\eta_{kj} \frac{\partial E}{\partial w_{kj}^3} = -\eta_{kj} \frac{\partial E}{\partial O_k^3} \frac{\partial O_k^3}{\partial w_{kj}^3} = \eta_{kj} \delta_k O_j^2 \quad (5.6)$$

$$\Delta w_j^2 = -\eta_j \frac{\partial E}{\partial w_j^2} = -\eta_j \frac{\partial E}{\partial O_k^3} \frac{\partial O_k^3}{\partial O_j^2} \frac{\partial O_j^2}{\partial w_j^2} = \eta_j \delta_k w_{kj}^3 P_j^2 \quad (5.8)$$

$$\Delta w_{ji}^2 = -\eta_{ji} \frac{\partial E}{\partial w_{ji}^2} = -\eta_{ji} \frac{\partial E}{\partial O_k^3} \frac{\partial O_k^3}{\partial O_j^2} \frac{\partial O_j^2}{\partial w_{ji}^2} = \eta_{ji} \delta_k w_{kj}^3 Q_{ji}^2 \quad (5.10)$$

### ■ 誤差適應法則

$$\delta_k = e_m + p e_m \quad (5.12)$$

# 五、遞迴式類神經網路控制的理論基礎(續)



## □ 網路收斂性分析

- 採用線上可調變的學習速率
- 可調變學習速率的推導是以使用誤差適應法則為基礎的離散型Lyapunov函數來分析，以確保軌跡追隨誤差的收斂性



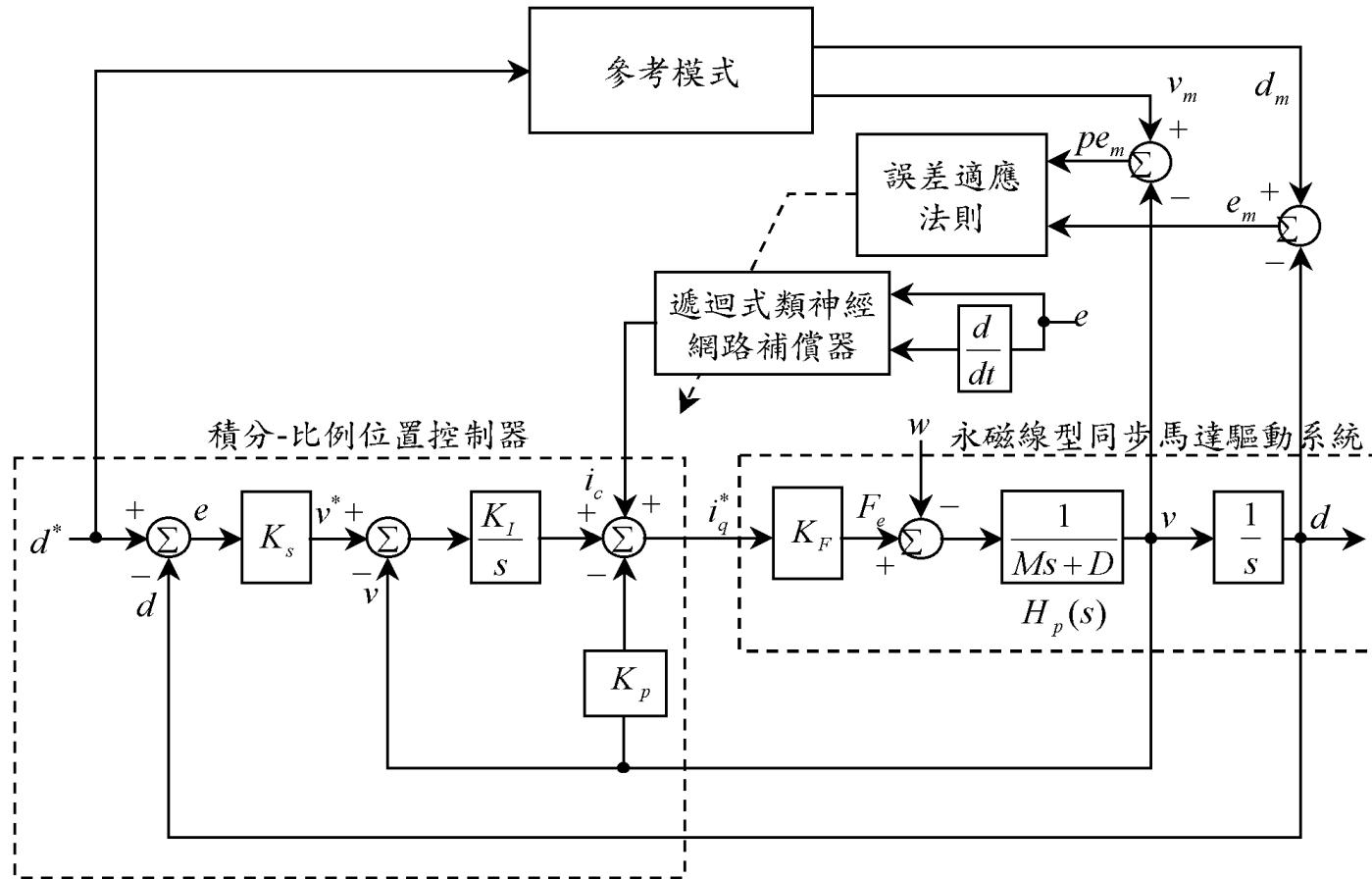
## □補償器

- 適用狀況：受控系統產生大幅之未確定量時，改善積分-比例位置控制器的追隨響應規格
- 設計方法：以參考模式和動子位置之誤差及其導數輸入至遞迴式類神經網路補償器，網路輸出一補償訊號以補償積分-比例位置控制器所造成的追隨誤差量

# 六、遞迴式類神經網路之強健控制系統(續)



補償器控制方塊圖



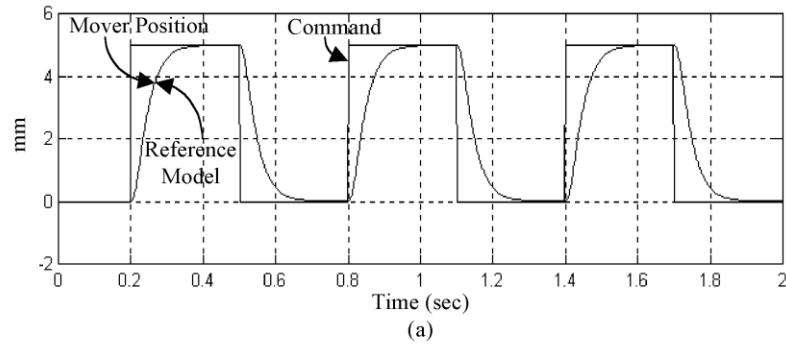
# 六、遞迴式類神經網路之強健控制系統(續)



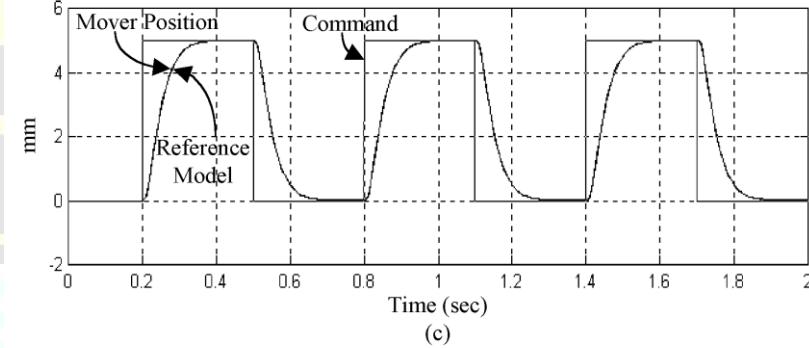
## □ 模擬結果

### ■ 補償器

標準動子質量



4 倍動子質量



(a)

(c)

(b)

(d)

圖 6.4

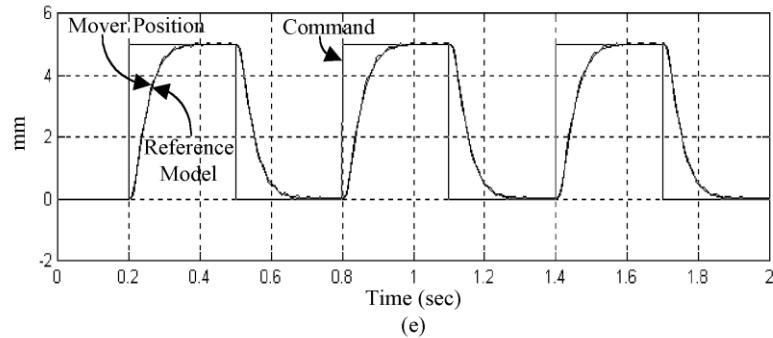
# 六、遞迴式類神經網路之強健控制系統(續)



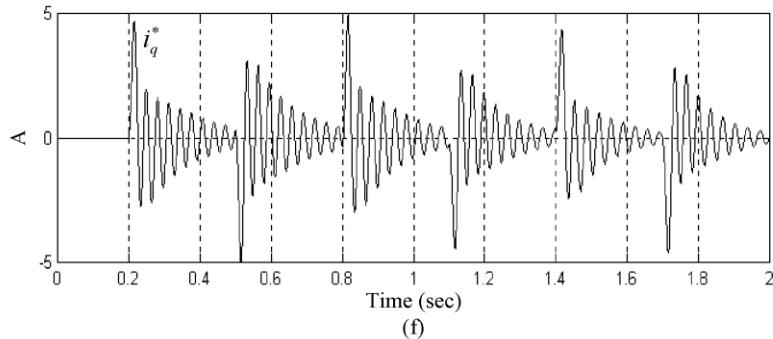
## □ 模擬結果(續)

### 補償器

6 倍動子質量

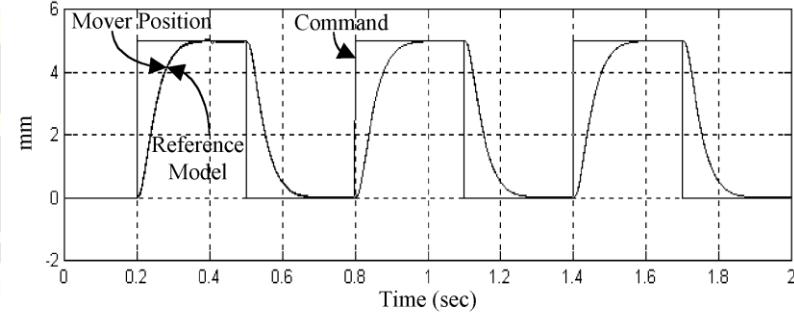


(e)

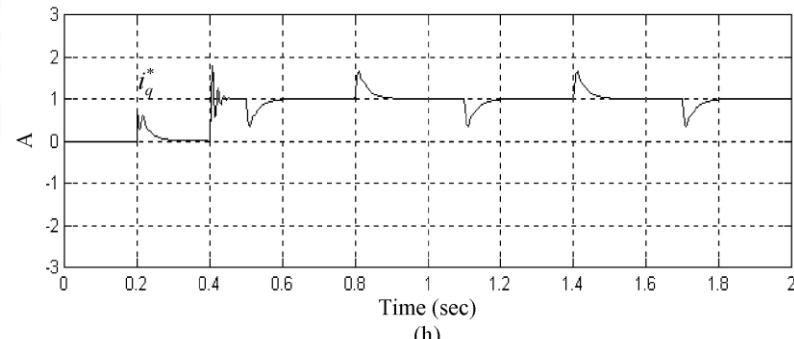


(f)

0.4 秒加負載



(g)



(h)

圖 6.4(續)

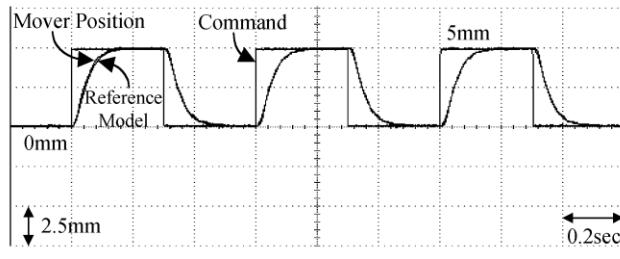
# 六、遞迴式類神經網路之強健控制系統(續)



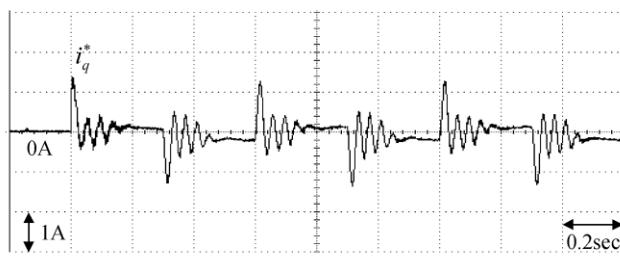
## □ 實測結果

### ■ 補償器

#### 標準動子質量

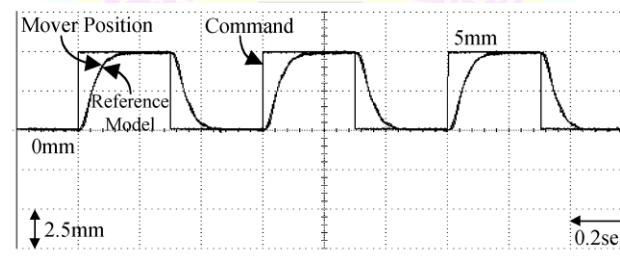


(a)

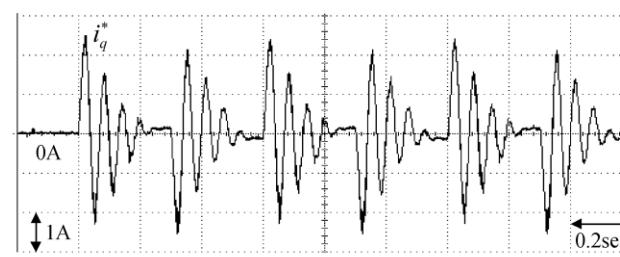


(b)

#### 4 倍動子質量

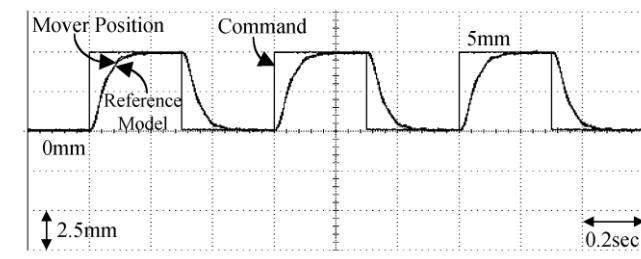


(c)

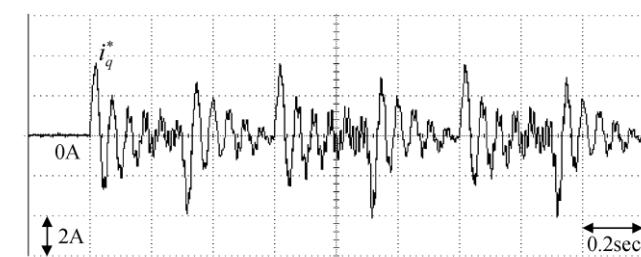


(d)

#### 6 倍動子質量



(e)



(f)

圖 6.7

# 六、遞迴式類神經網路之強健控制系統(續)



## □ 控制器

- 適用狀況：追隨週期性的步階命令或弦波命令，或是受控系統有參數變化和外來負載干擾時保持系統的追隨響應規格
- 設計方法：以參考模式和動子位置之誤差及其導數輸入至遞迴式類神經網路控制器，網路之輸出即為馬達推力的命令電流值

# 六、遞迴式類神經網路之強健控制系統(續)



## 控制器控制方塊圖

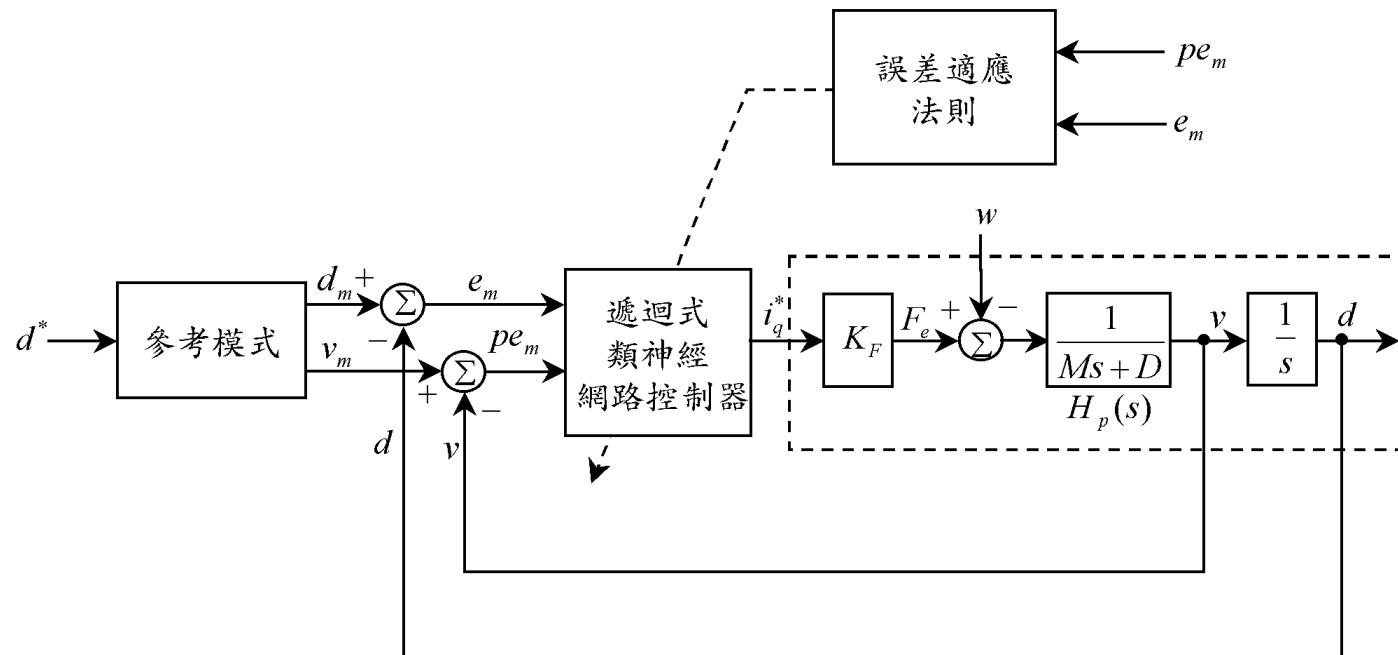


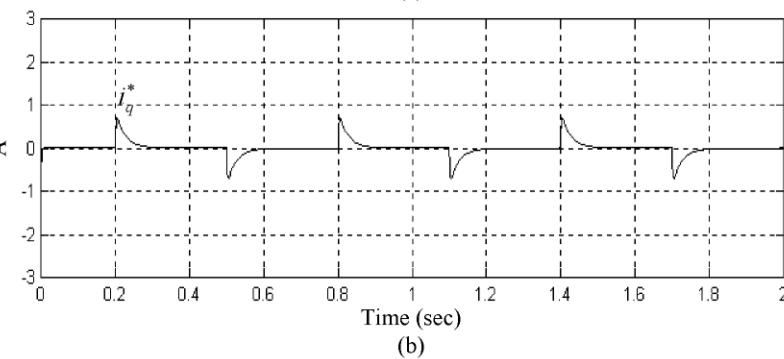
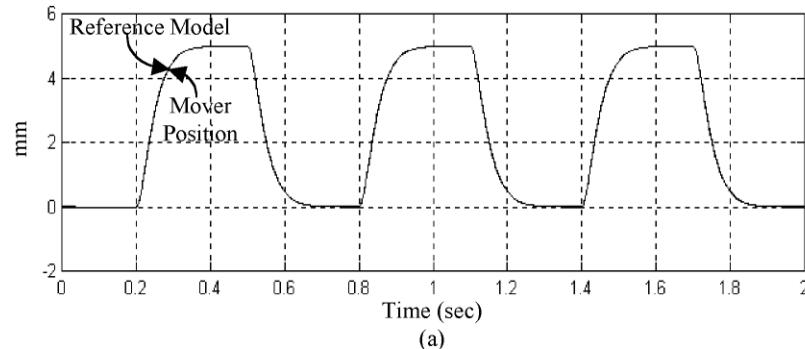
圖 6.2

# 六、遞迴式類神經網路之強健控制系統(續)

## □ 模擬結果

### ■ 控制器

標準動子質量



3 倍動子質量

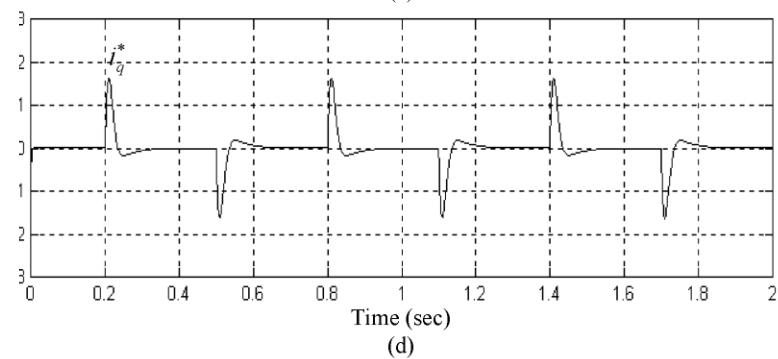
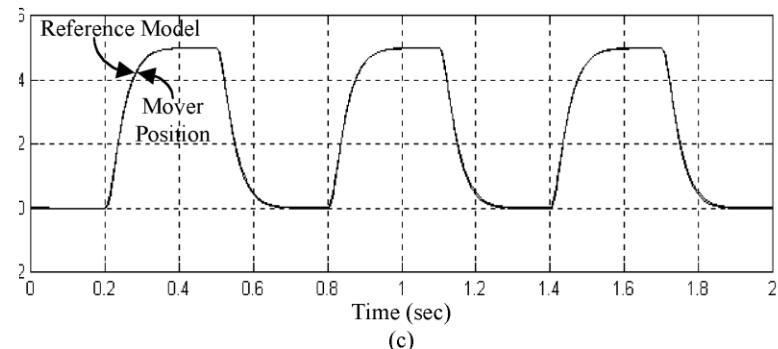


圖 6.5

# 六、遞迴式類神經網路之強健控制系統(續)

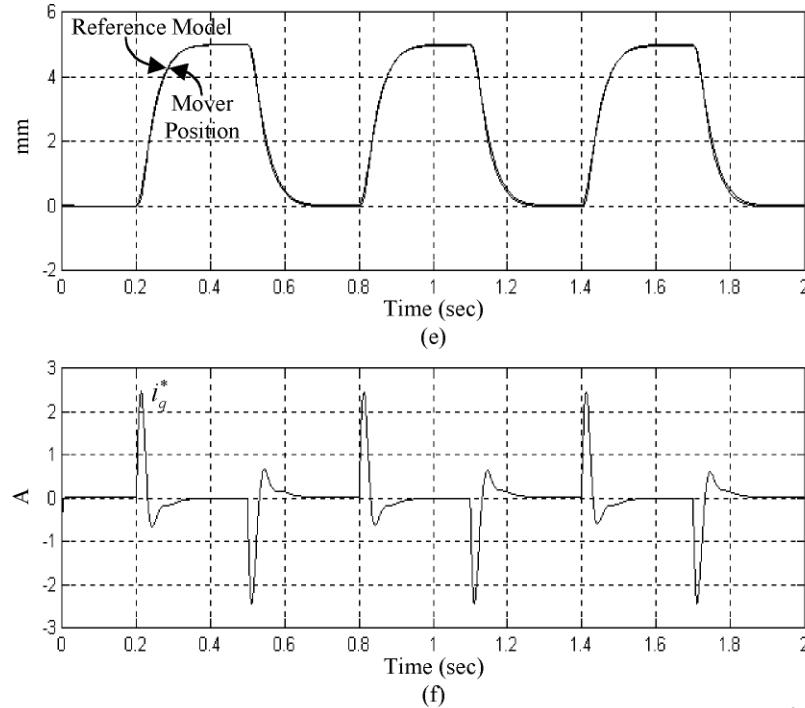


國立中央大學

## □ 模擬結果(續)

### ■ 控制器

4.5 倍動子質量



0.4 秒加負載

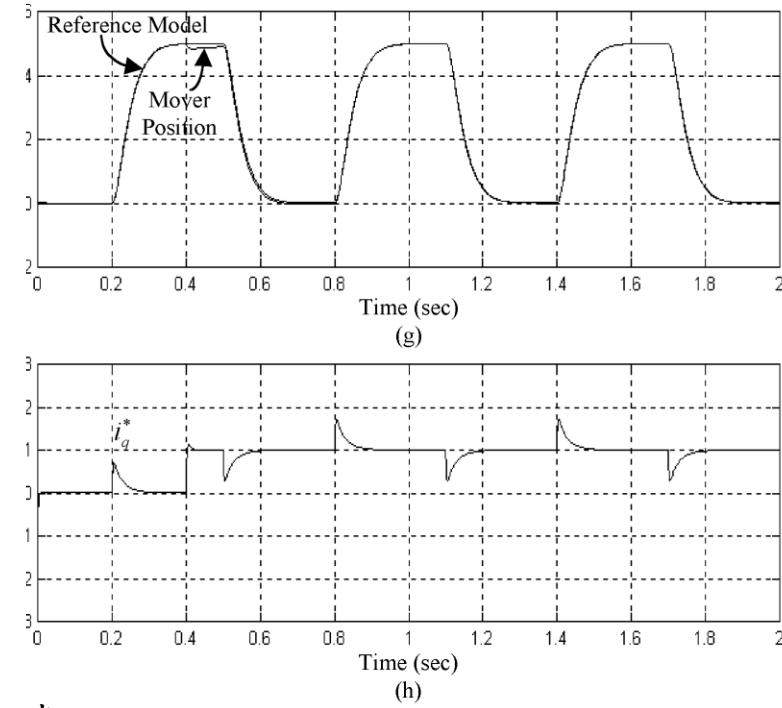


圖 6.5(續)

# 六、遞迴式類神經網路之強健控制系統(續)



國立中央大學

## □ 模擬結果(續)

### ■ 控制器

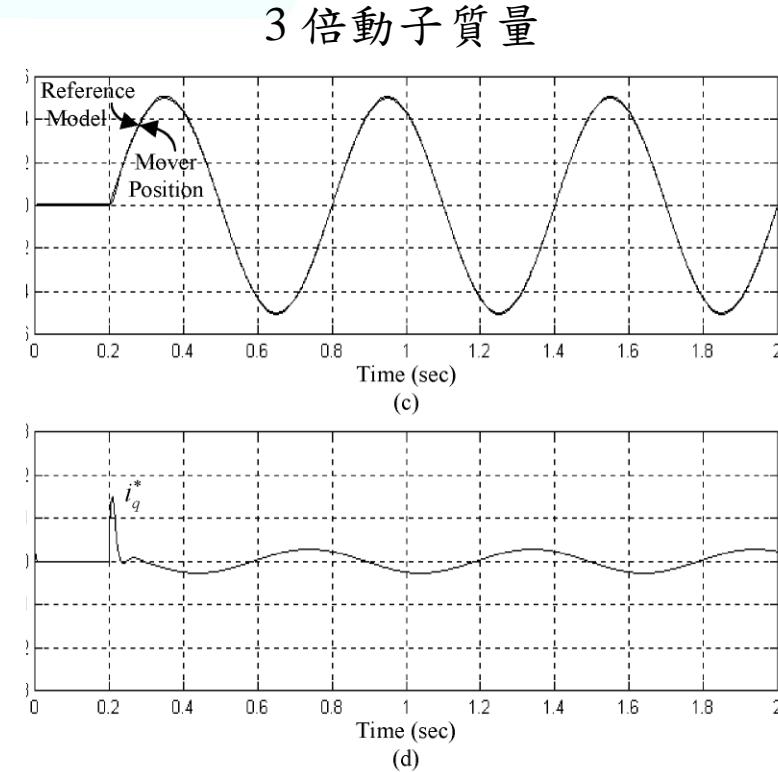
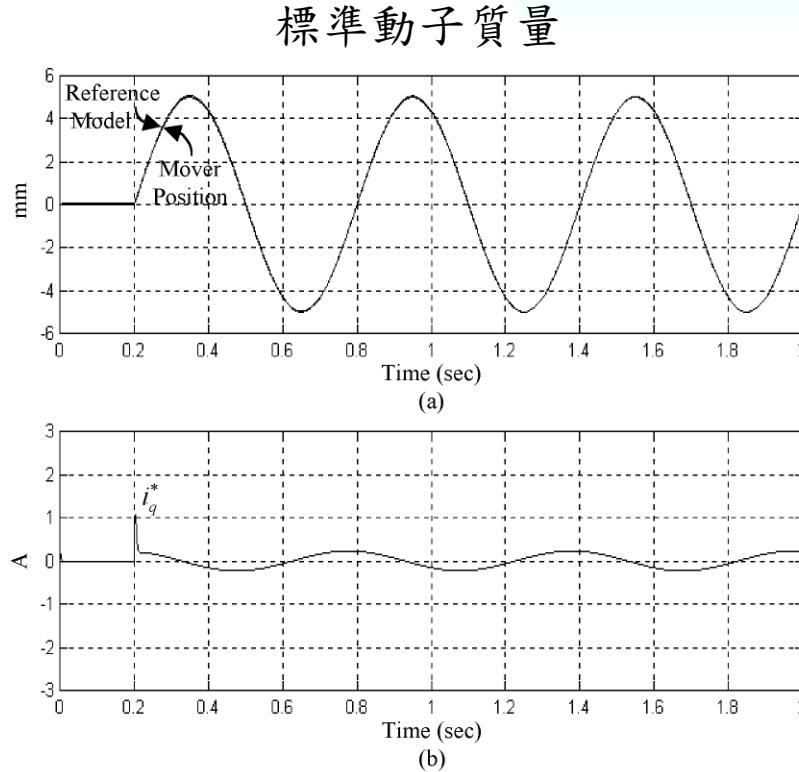


圖 6.6

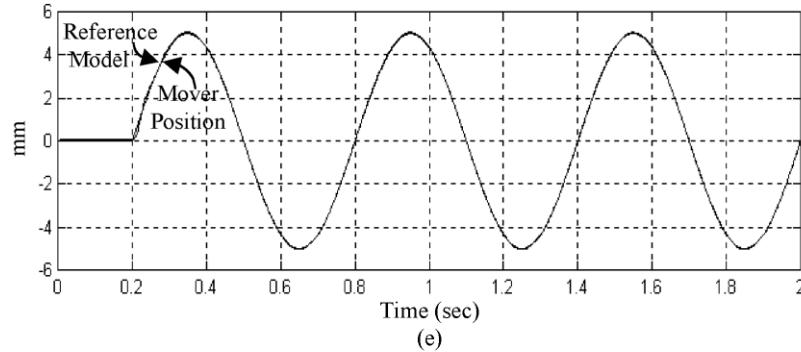
# 六、遞迴式類神經網路之強健控制系統(續)



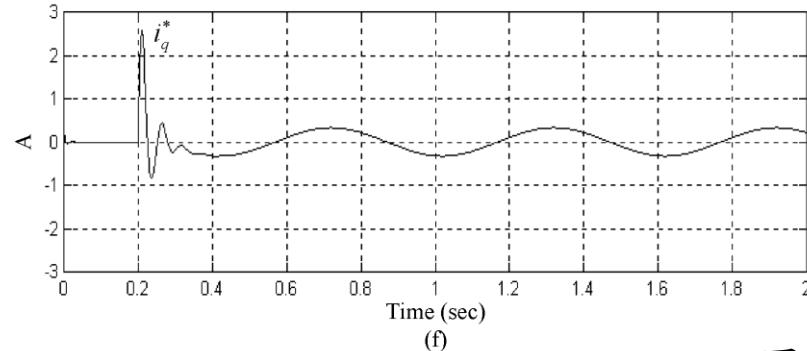
## □ 模擬結果(續)

### ■ 控制器

4.5 倍動子質量

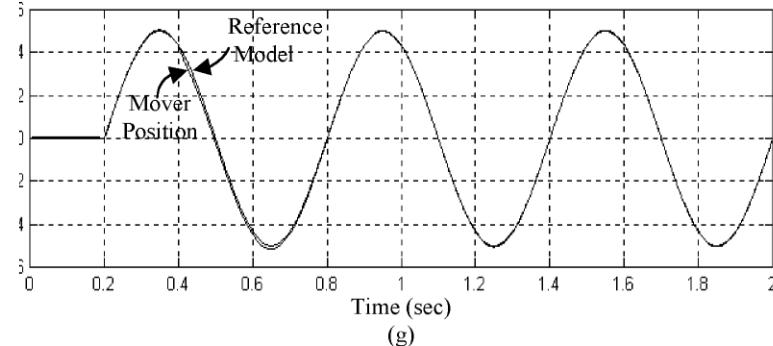


(e)

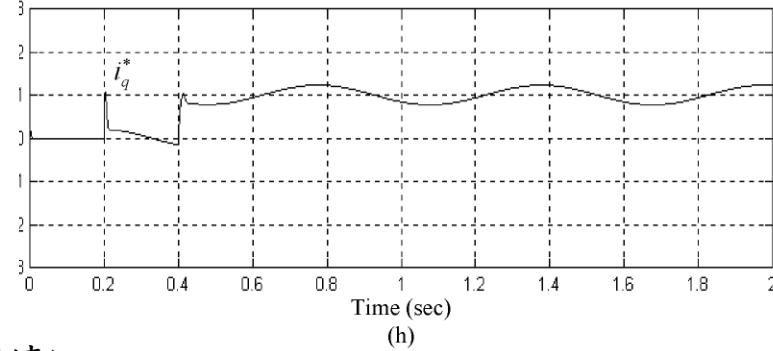


(f)

0.4 秒加負載



(g)



(h)

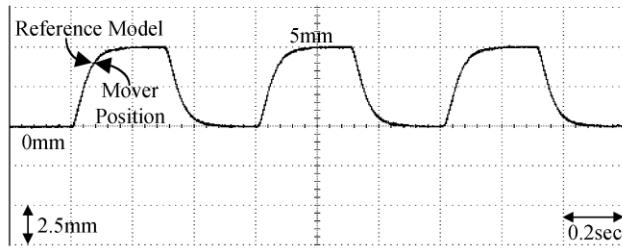
圖 6.6(續)

# 六、遞迴式類神經網路之強健控制系統(續)

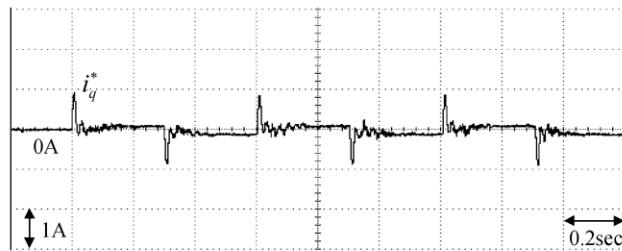
## □ 實測結果

### 控制器

標準動子質量

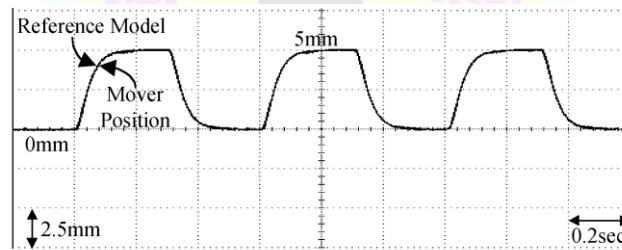


(a)

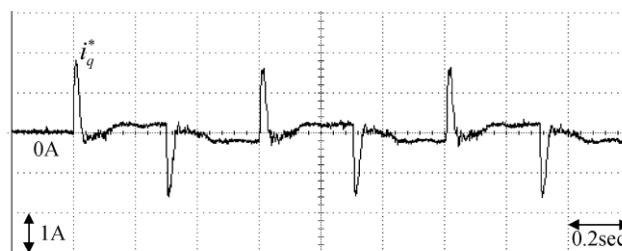


(b)

3倍動子質量

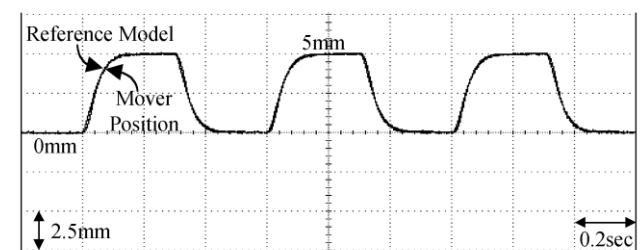


(c)

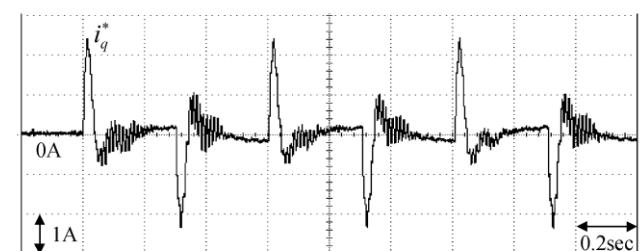


(d)

4.5倍動子質量



(e)



(f)

圖 6.8

# 六、遞迴式類神經網路之強健控制系統(續)

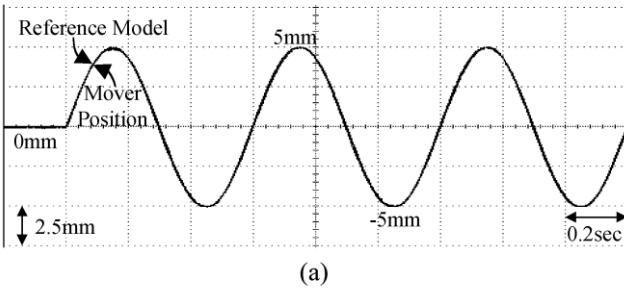


國立中央大學

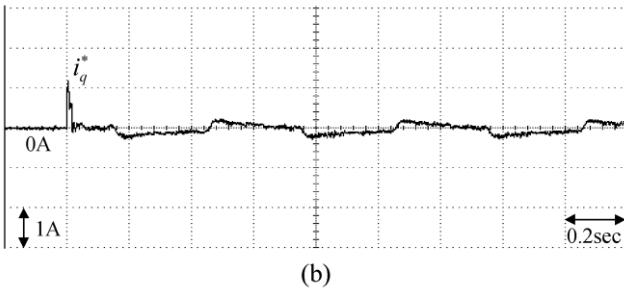
## □ 實測結果(續)

### ■ 控制器

標準動子質量

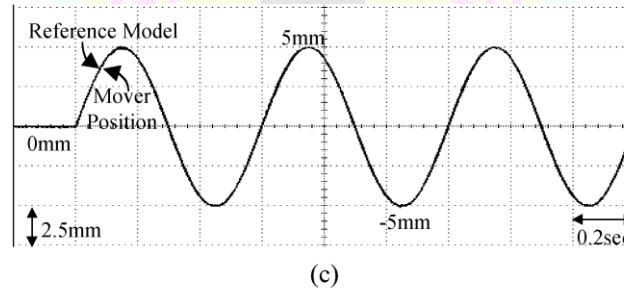


(a)

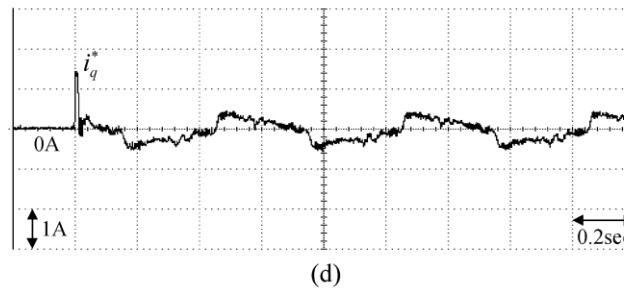


(b)

3倍動子質量

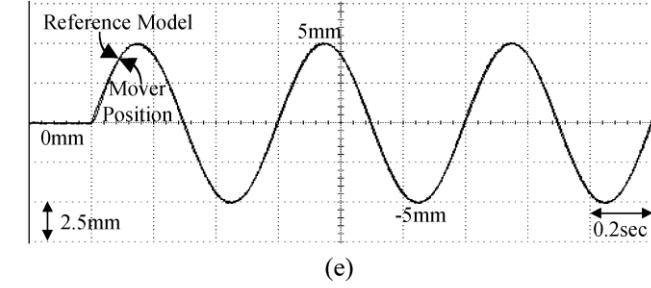


(c)

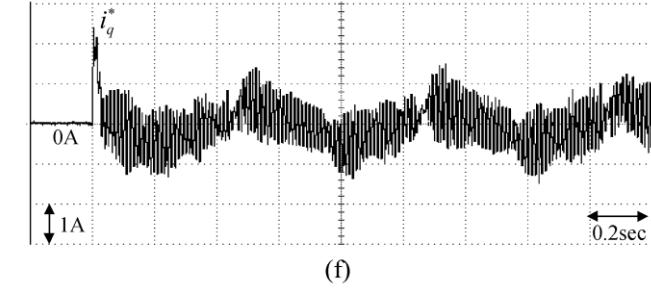


(d)

4.5倍動子質量



(e)



(f)

圖 6.9



# 七、利用遞迴式類神經網路之適應混合型控制系統

國立中央大學

## □混合型控制系統

- 『遞迴式類神經網路控制器：表示為泰勒級數展開式』
- 『補償控制器：補償最佳控制法則與遞迴式類神經網路之間的近似誤差及泰勒高階項』
- 『永磁線型同步馬達驅動系統的動態方程式重寫如下：』

$$\dot{v} = -\frac{D}{M}v + \frac{K_F}{M}i_q^* - \frac{1}{M}w = A_P v + B_P U_T + C_P w \quad (7.1)$$

- 『最佳控制法則定義』

$$U_T^* = \frac{1}{B_P} [-A_P v - C_P w + \dot{v}_m + KE] \quad (7.3)$$

- 『系統的控制法則』

$$U_T = U_{RNN} + U_S \quad (7.5)$$



## 七、利用遞迴式類神經網路之適應混合型控制系統(續)

國立中央大學

以遞迴式類神經網路的輸出來表示控制力，可表示如下：

$$U_{RFNN}(E|\Theta) = W^T \Gamma \quad (7.6)$$

發展補償控制法則，定義一最小近似誤差

$$\varepsilon = U^* - U_{RNN}(E|\Theta^*) \quad (7.8)$$

其中  $\Theta^*$  表示達到最小近似誤差時的理想權重值向量，並且假設最小近似誤差  $\varepsilon$  的絕對值小於一極小的正數，即  $|\varepsilon| < \delta$

## 七、利用遞迴式類神經網路之適應混合型控制系統(續)

對  $U_{RNN}(E|\Theta^*)$  之  $\Theta$  取泰勒級數展開式，則可獲得如下之結果

$$U_{RNN}(E|\Theta^*) - U_{RNN}(E|\Theta) = (\Theta^* - \Theta)^T \left[ \frac{\partial U_{RNN}(E|\Theta)}{\partial \Theta} \right] + H \quad (7.10)$$

其中  $H$  表示泰勒級數展開式的高階項，並且假設是有邊界的，即  $|H| < \phi$

適應法則和補償控制器的設計如下：

$$\dot{\Theta} = \gamma E^T P B_m \frac{\partial U_{RNN}(E|\Theta)}{\partial \Theta} \quad (7.14)$$

$$U_S = (\delta + \phi) \operatorname{sgn}(E^T P B_m) \quad (7.15)$$

## 七、利用遞迴式類神經網路之適應混合型控制系統(續)

遞迴式類神經網路三個可調變權重值的適應法則如下：

$$\dot{w}_{kj}^3 = \gamma \mathbf{E}^T \mathbf{PB}_m \frac{\partial U_{RNN}}{\partial O_k^3} \frac{\partial O_k^3}{\partial net_k^3} \frac{\partial net_k^3}{\partial w_{jk}^3} = \gamma \mathbf{E}^T \mathbf{PB}_m x_j^3 \quad (7.16)$$

$$\begin{aligned} \dot{w}_j^2 &= \gamma \mathbf{E}^T \mathbf{PB}_m \frac{\partial U_{RNN}}{\partial O_k^3} \frac{\partial O_k^3}{\partial net_k^3} \frac{\partial net_k^3}{\partial O_j^2} \frac{\partial O_j^2}{\partial net_j^2} \frac{\partial net_j^2}{\partial w_j^2} \\ &= \gamma \mathbf{E}^T \mathbf{PB}_m w_{kj}^3 P_j^2 \end{aligned} \quad (7.17)$$

$$\begin{aligned} \dot{w}_{ji}^2 &= \gamma \mathbf{E}^T \mathbf{PB}_m \frac{\partial U_{RNN}}{\partial O_k^3} \frac{\partial O_k^3}{\partial net_k^3} \frac{\partial net_k^3}{\partial O_j^2} \frac{\partial O_j^2}{\partial net_j^2} \frac{\partial net_j^2}{\partial w_{ji}^2} \\ &= \gamma \mathbf{E}^T \mathbf{PB}_m w_{kj}^3 Q_{ji}^2 \end{aligned} \quad (7.18)$$

## □混合型控制系統方塊圖

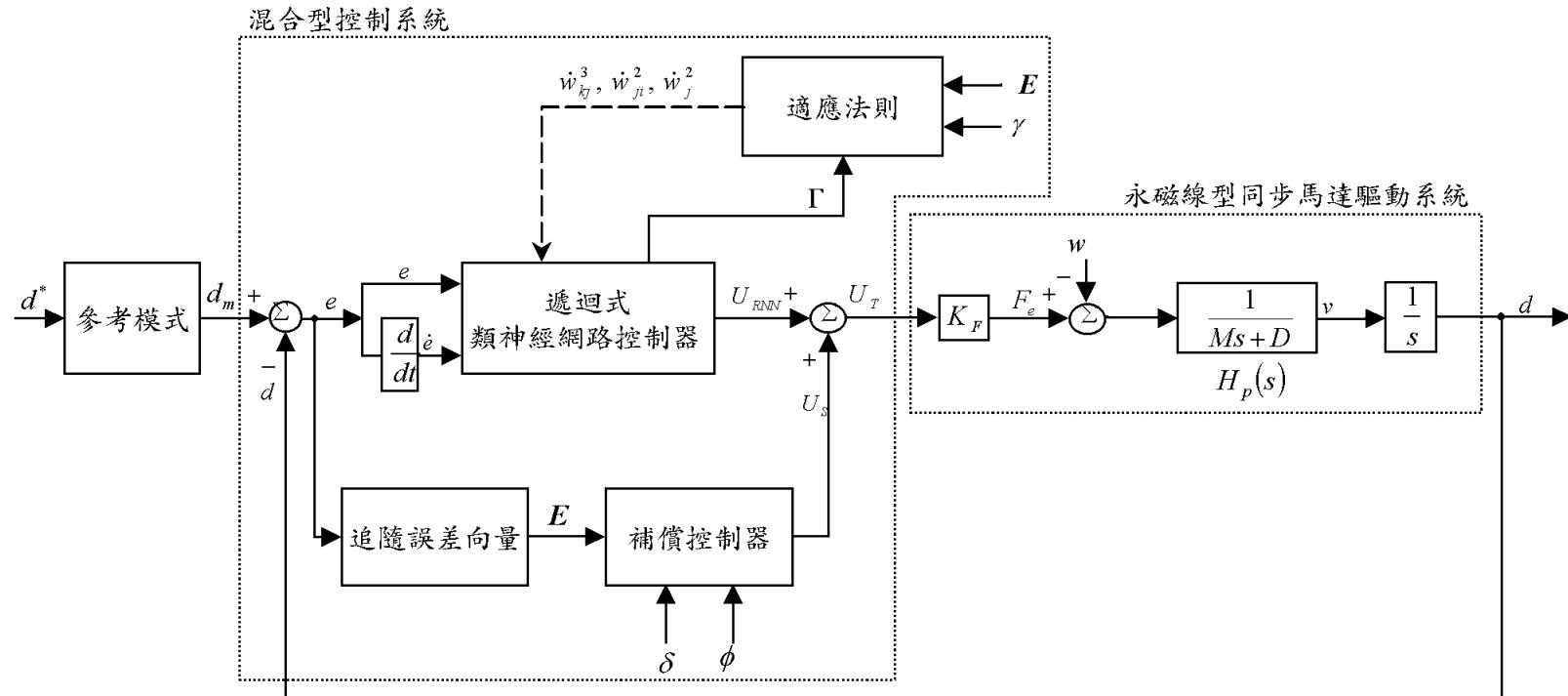


圖 7.1



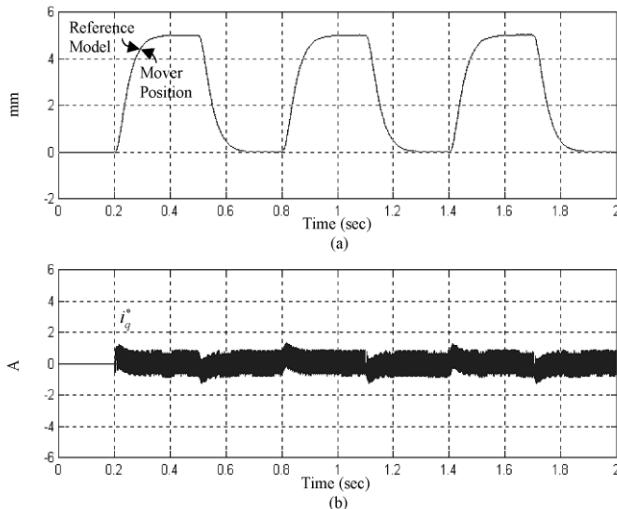
# 七、利用遞迴式類神經網路之適應混合型控制系統(續)

國立中央大學

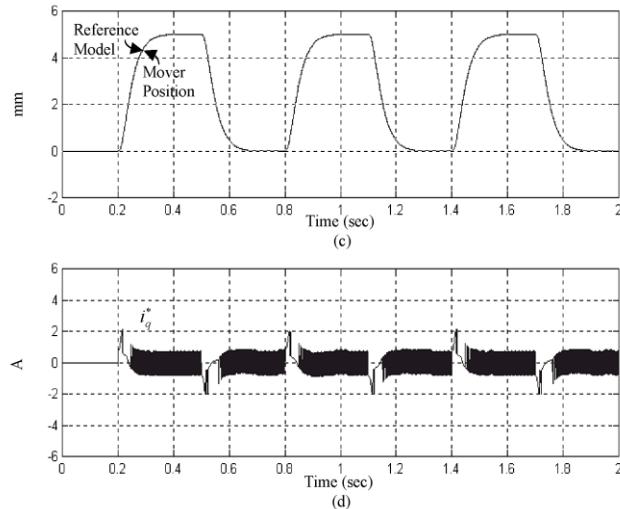
## □ 模擬結果

### 混合控制系統

標準動子質量



3倍動子質量



1秒加負載

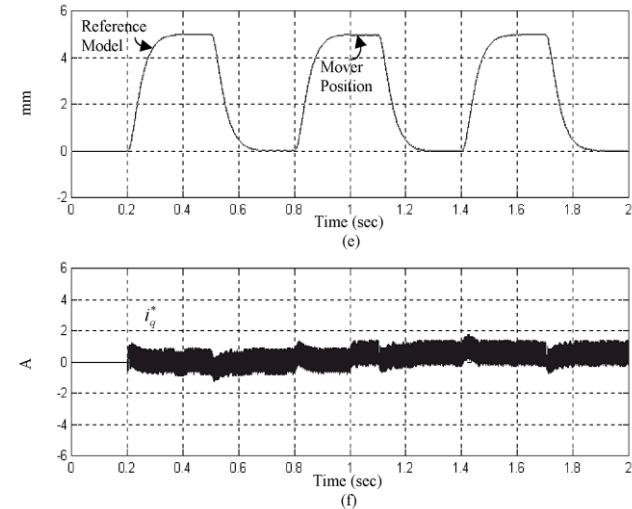


圖 7.3



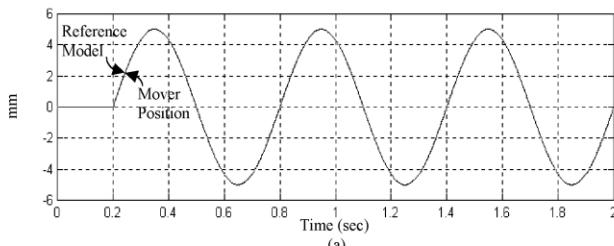
# 七、利用遞迴式類神經網路之適應混合型控制系統(續)

國立中央大學

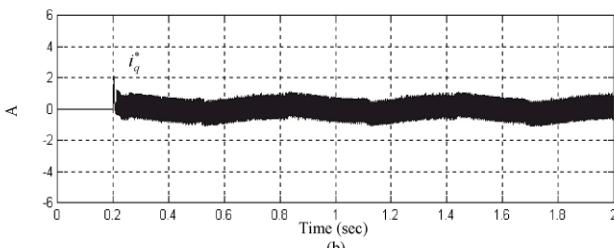
## □ 模擬結果(續)

### 混合控制系統

標準動子質量

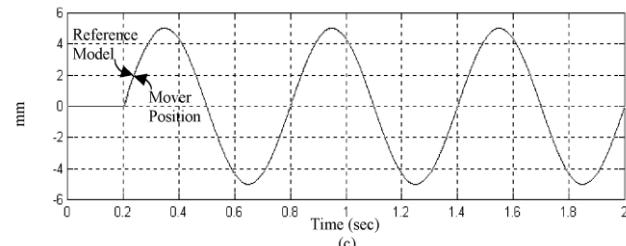


(a)

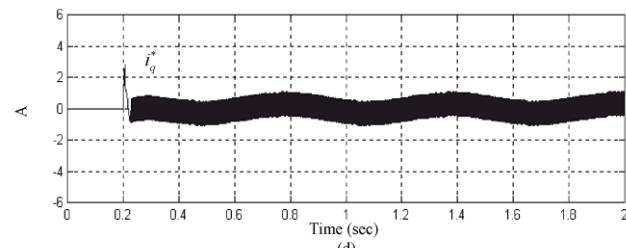


(b)

3倍動子質量

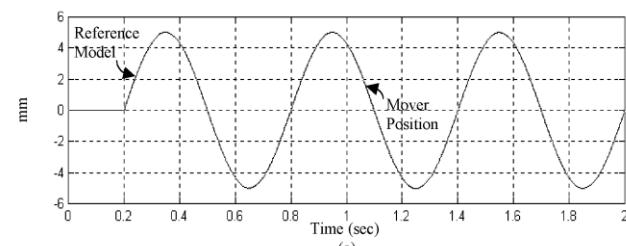


(c)

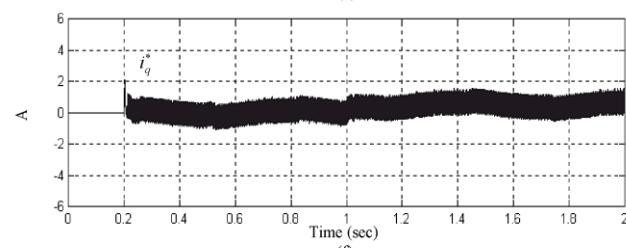


(d)

1秒加負載



(e)



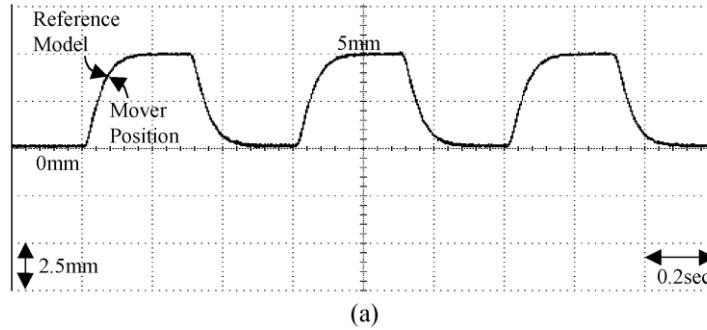
(f)

圖 7.4

## □ 實測結果

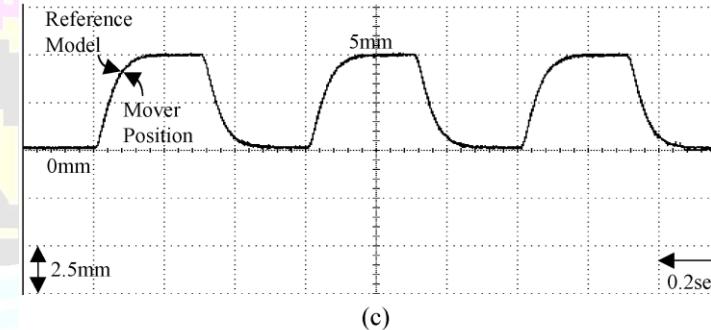
### 混合控制系統

標準動子質量

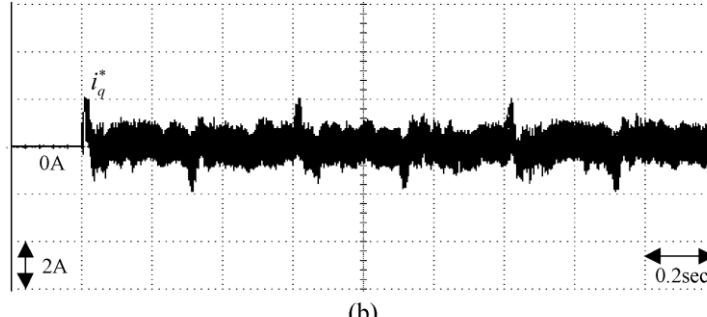


(a)

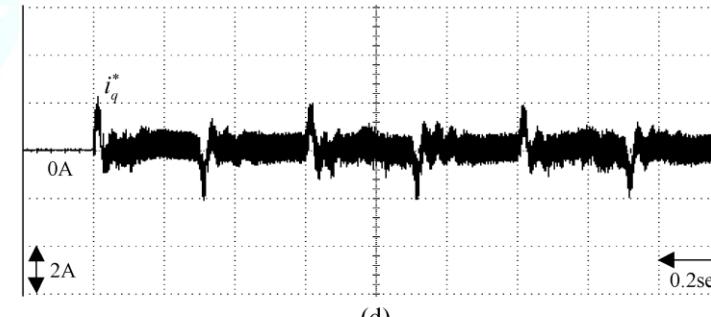
3 倍動子質量



(c)



(b)



(d)

圖 7.7

## □ 實測結果(續)

### 混合控制系統

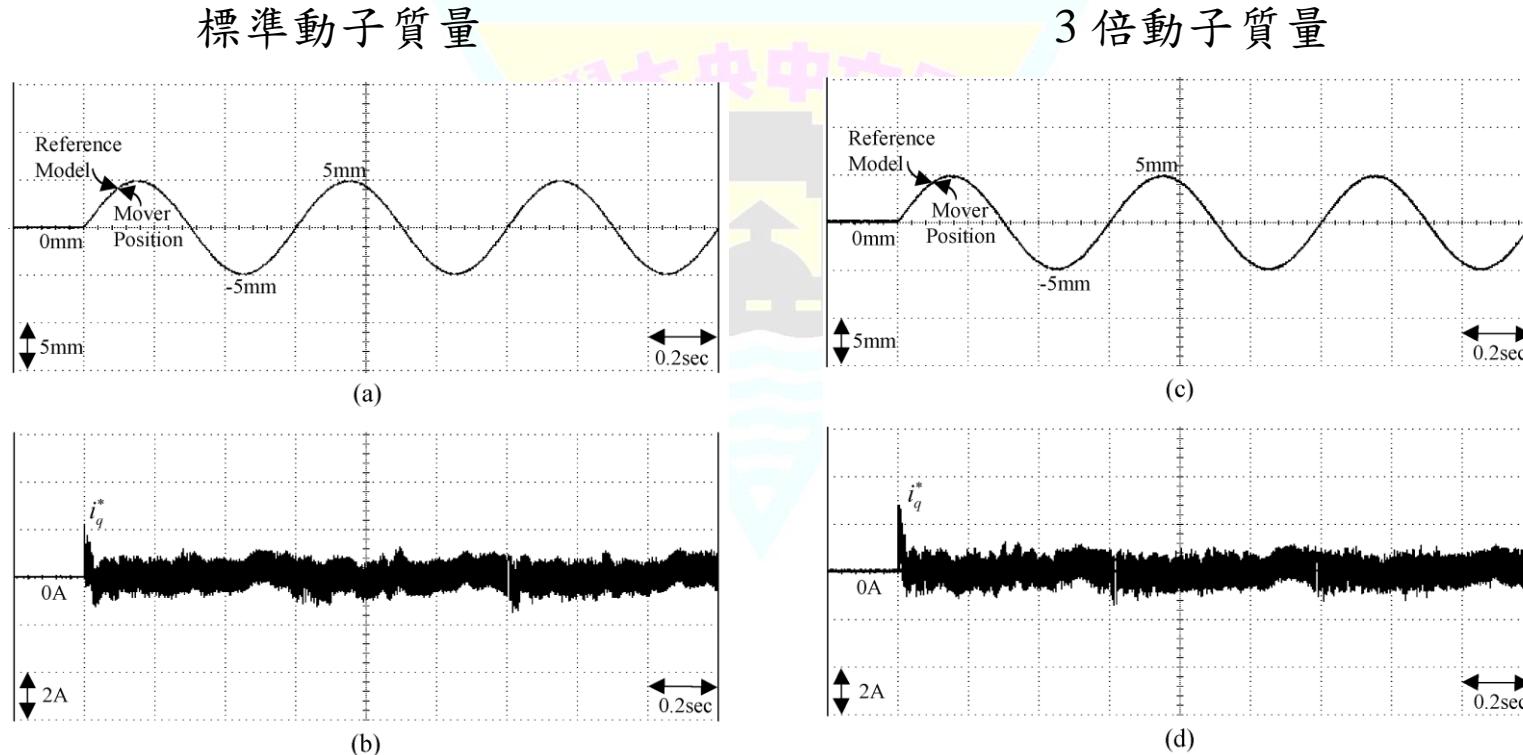


圖 7.8

## 七、利用遞迴式類神經網路之適應混合型控制系統(續)

### □適應混合型控制系統

〔近似誤差與泰勒高階項之邊限值的選擇方式，將嚴重影響著控制力的大小〕

〔 $\delta$  和  $\phi$  的適應法則設計如下：〕

$$\hat{\delta}(t) = \lambda |E^T PB_m| \quad (7.26)$$

$$\hat{\phi}(t) = \beta |E^T PB_m| \quad (7.27)$$

〔將  $\hat{\delta}$  及  $\hat{\phi}$  取代(7.15)式之 $\delta$  及 $\phi$ ，則補償控制器表示如下：〕

$$U_S = (\hat{\delta} + \hat{\phi}) \operatorname{sgn}(E^T PB_m) \quad (7.28)$$

## □ 適應混合型控制系統方塊圖

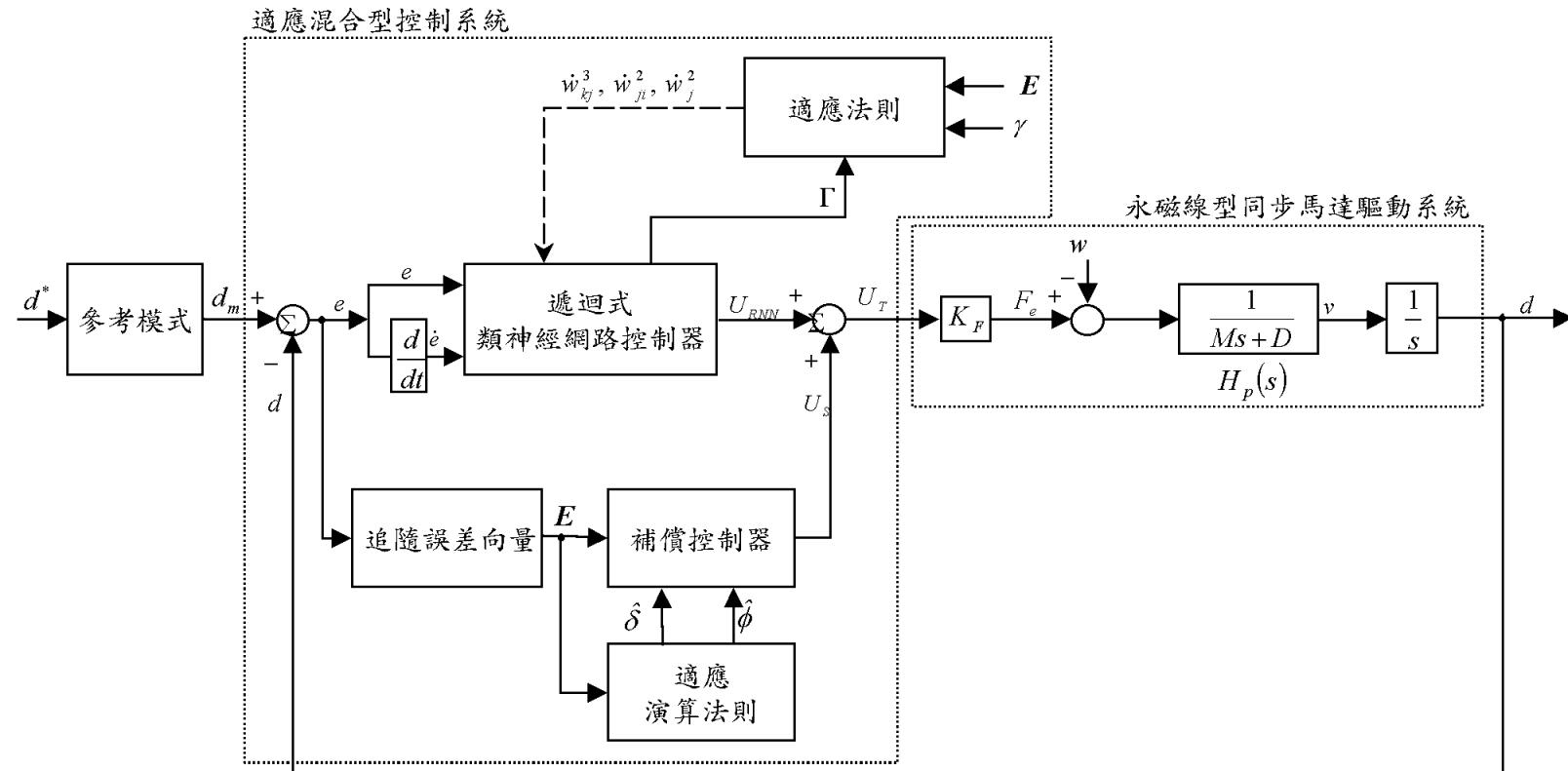
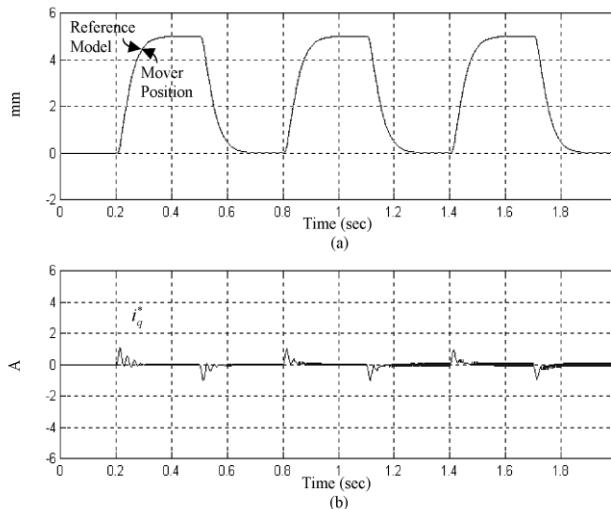


圖 7.2

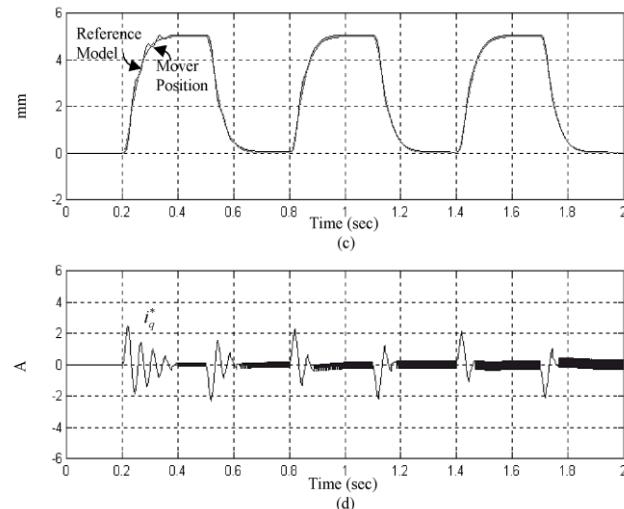
## □ 模擬結果

## ■ 適應混合控制系統

標準動子質量



3倍動子質量



1秒加負載

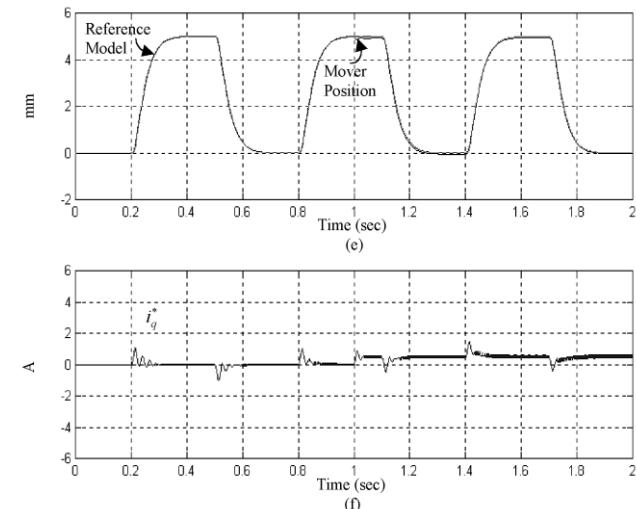


圖 7.5



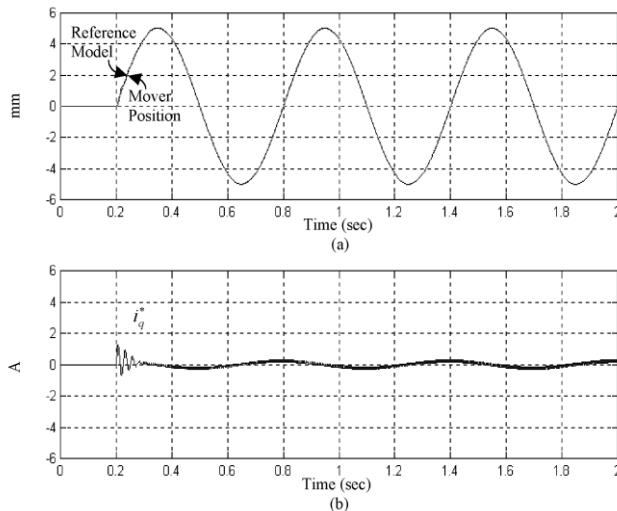
# 七、利用遞迴式類神經網路之適應混合型控制系統(續)

國立中央大學

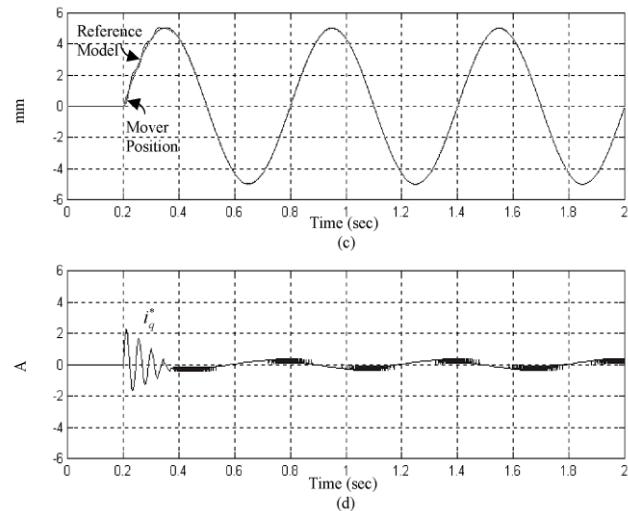
## □ 模擬結果(續)

### ■ 適應混合控制系統

標準動子質量



3倍動子質量



1秒加負載

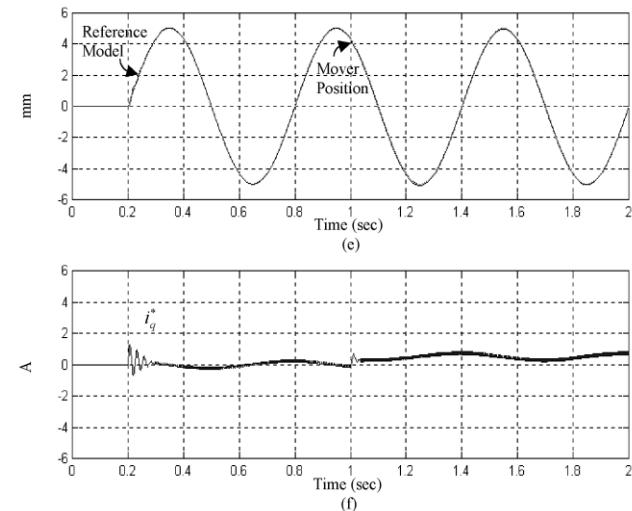


圖 7.6

## □ 實測結果

### ■ 適應混合控制系統

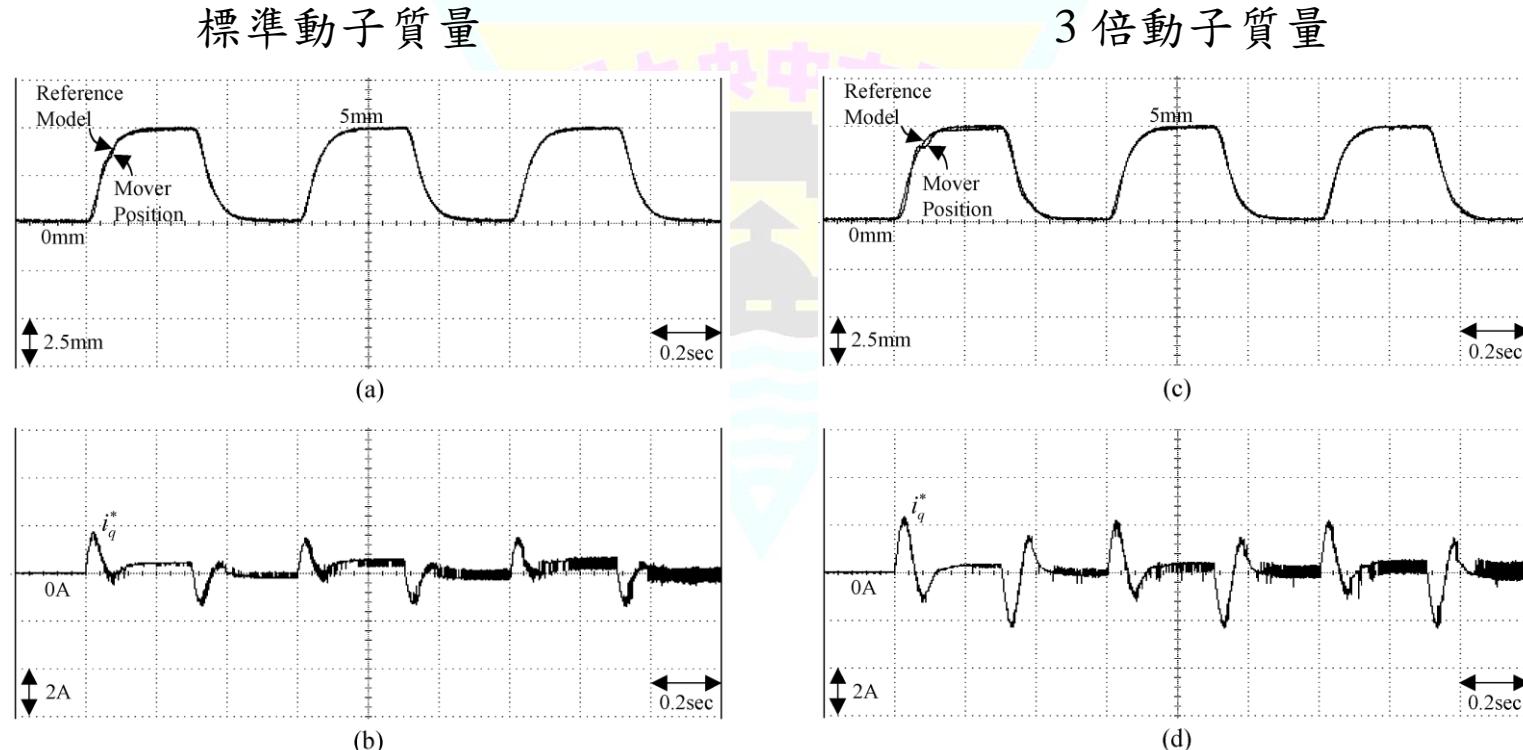
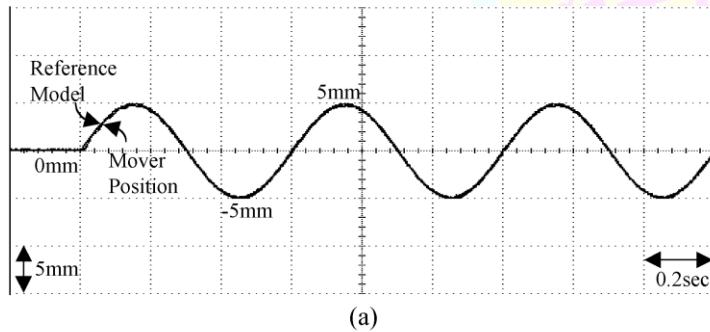


圖 7.9

## □ 實測結果(續)

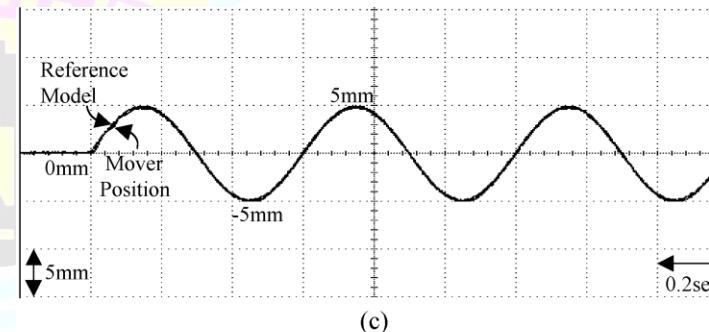
### ■ 適應混合控制系統

標準動子質量

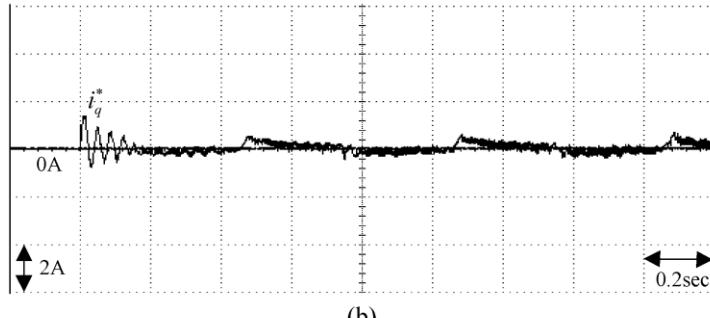


(a)

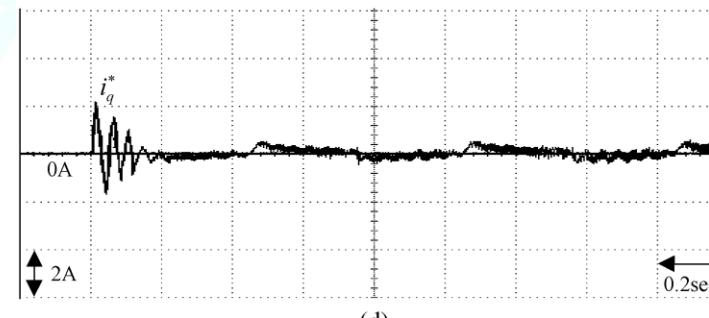
3倍動子質量



(c)



(b)



(d)

圖 7.10

# 八、遞迴式模糊類神經網路控制的理論基礎



## □ 網路架構圖

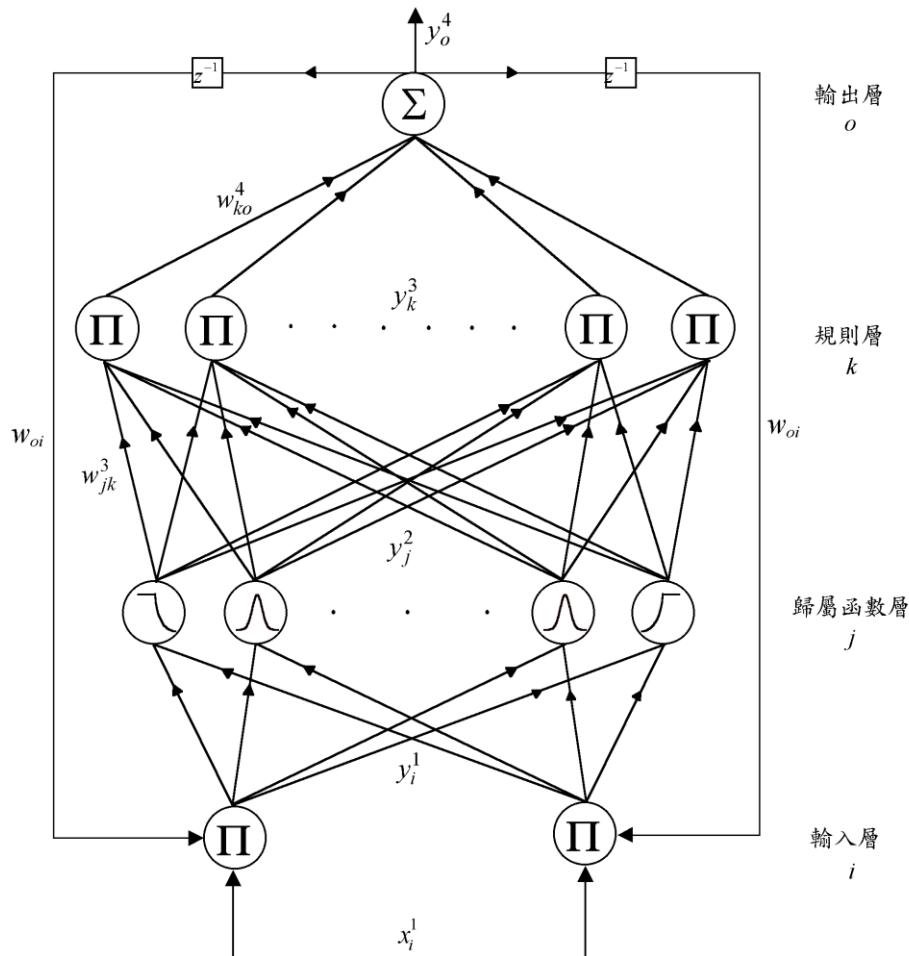


圖 8.1

# 八、遞迴式模糊類神經網路控制的理論基礎(續)



## □ 網路描述

### ■ 輸入層

$$\begin{aligned} net_i^1(N) &= \prod_o x_i^1(N) w_{oi} y_o^4(N-1) \\ y_i^1(N) &= f_i^1(net_i^1(N)) = net_i^1(N), \quad i = 1, 2 \end{aligned} \tag{8.1}$$

### ■ 歸屬函數層

$$\begin{aligned} net_j^2(N) &= -\frac{(x_i^2 - m_{ij})^2}{(\sigma_{ij})^2} \\ y_j^2(N) &= f_j^2(net_j^2(N)) = \exp(net_j^2(N)), \quad j = 1, \dots, n \end{aligned} \tag{8.2}$$

# 八、遞迴式模糊類神經網路控制的理論基礎(續)



## 規則層

$$\begin{aligned} net_k^3(N) &= \prod_j w_{jk}^3 x_j^3(N) \\ y_k^3(N) &= f_k^3(net_k^3(N)) = net_k^3(N), \quad k = 1, \dots, l \end{aligned} \quad (8.3)$$

## 輸出層

$$\begin{aligned} net_o^4 &= \sum_k w_{ko}^4 x_k^4 \\ y_o^4(N) &= f_o^4(net_o^4(N)) = net_o^4(N), \quad o = 1 \end{aligned} \quad (8.4)$$

# 八、遞迴式模糊類神經網路控制的理論基礎(續)



## □ 線上學習法則

### ■ 權重值更新值

$$\Delta w_{ko}^4 = -\eta_w \frac{\partial E}{\partial w_{ko}^4} = \left[ -\eta_w \frac{\partial E}{\partial y_o^4} \frac{\partial y_o^4}{\partial net_o^4} \right] \left( \frac{\partial net_o^4}{\partial w_{ko}^4} \right) = \eta_w \delta_o^4 x_k^4 \quad (8.7)$$

$$\begin{aligned} \Delta m_{ij} &= -\eta_m \frac{\partial E}{\partial m_{ij}} = \left[ -\eta_m \frac{\partial E}{\partial y_j^2} \frac{\partial y_j^2}{\partial net_j^2} \frac{\partial net_j^2}{\partial m_{ij}} \right] \\ &= \eta_m \delta_j^2 \frac{2(x_i^2 - m_{ij})}{(\sigma_{ij})^2} \end{aligned} \quad (8.11)$$



## 八、遞迴式模糊類神經網路控制的理論基礎(續)

$$\begin{aligned}\Delta \sigma_{ij} &= -\eta_\sigma \frac{\partial E}{\partial \sigma_{ij}} = \left[ -\eta_\sigma \frac{\partial E}{\partial y_j^2} \frac{\partial y_j^2}{\partial net_j^2} \frac{\partial net_j^2}{\partial \sigma_{ij}} \right] \\ &= \eta_\sigma \delta_j^2 \frac{2(x_i^2 - m_{ij})^2}{(\sigma_{ij})^3} \quad (8.12)\end{aligned}$$

$$\begin{aligned}\Delta w_{oi} &= -\eta_r \frac{\partial E}{\partial w_{oi}} = \left[ -\eta_r \frac{\partial E}{\partial net_j^2} \frac{\partial net_j^2}{\partial y_i^1} \frac{\partial y_i^1}{\partial net_i^1} \frac{\partial net_i^1}{\partial w_{oi}} \right] \\ &= \sum_j \eta_r \delta_j^2 \frac{2(m_{ij} - x_i^2(N))}{(\sigma_{ij})^2} x_i^1(N) y_o^4(N-1) \quad (8.15)\end{aligned}$$

誤差適應法則

$$\delta_k = e_m + p e_m \quad (8.17)$$



### □ 網路收斂性分析

- 採用線上可調變的學習速率
- 可調變學習速率的推導是以使用誤差適應法則為基礎的離散型Lyapunov函數來分析，以確保軌跡追隨誤差的收斂性

# 九、利用遞迴式模糊類神經網路於積分-比例



## 位置控制器線上增益調整之控制系統

■ 系統參數變化和外來負載干擾對積分-比例位置控制系統的控制特性有很大影響

■ 根據(4.2)至(4.4)式，積分-比例位置控制器的控制增益參數 $K_I$ 及 $K_p$ 具有下列關係式

$$K_p = (\mu_1 + \mu_2 + \mu_3 - a) / (\mu_1\mu_2 + \mu_2\mu_3 + \mu_1\mu_3) K_I = P K_I \quad (9.1)$$

其中

$$P = (\mu_1 + \mu_2 + \mu_3 - a) / (\mu_1\mu_2 + \mu_2\mu_3 + \mu_1\mu_3) \quad (9.2)$$

# 九、利用遞迴式模糊類神經網路於積分-比例

## 位置控制器線上增益調整之控制系統(續)

遞迴式模糊類神經網路於積分-比例位置控制器  
線上增益調整之控制系統方塊圖

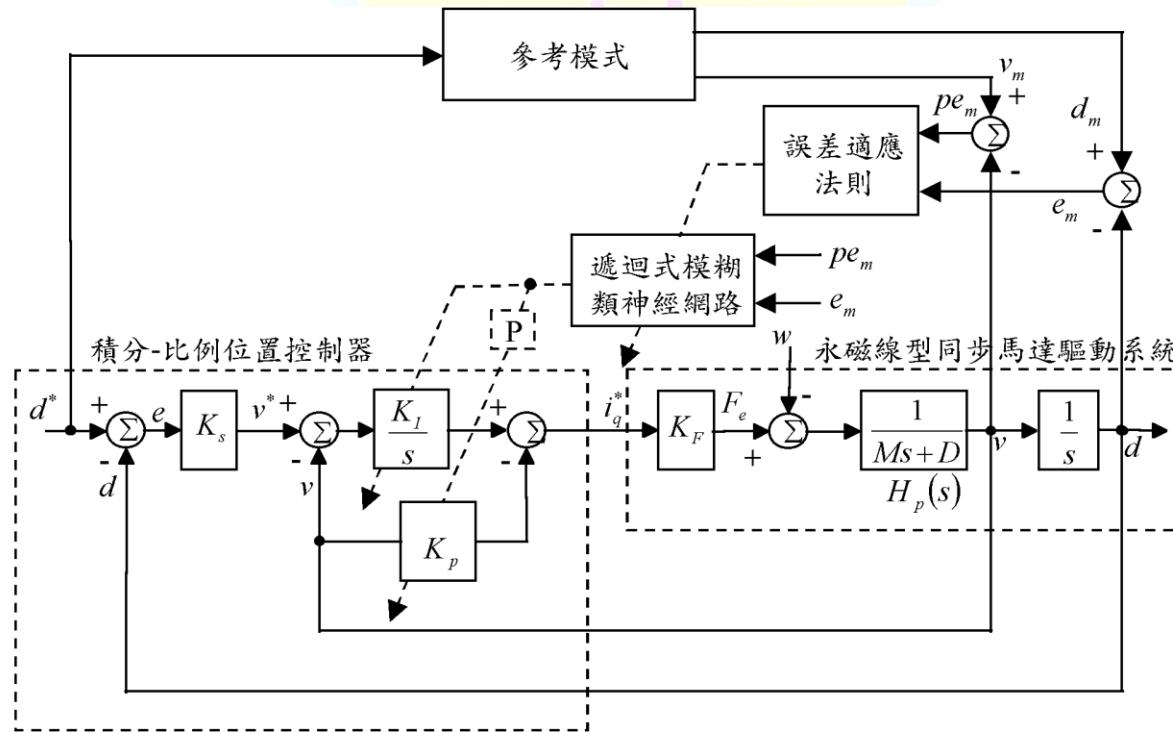


圖9.1

# 九、利用遞迴式模糊類神經網路於積分-比例

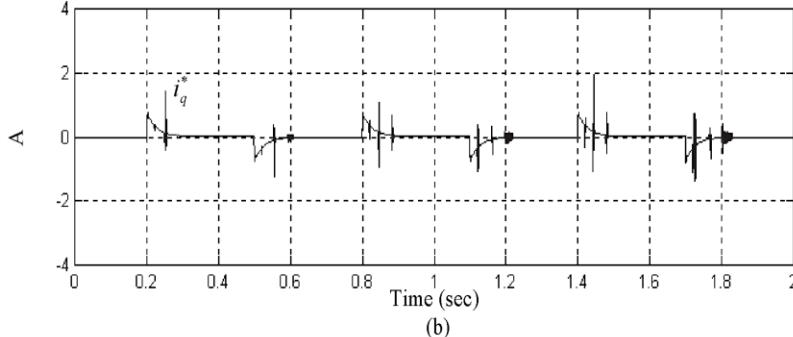
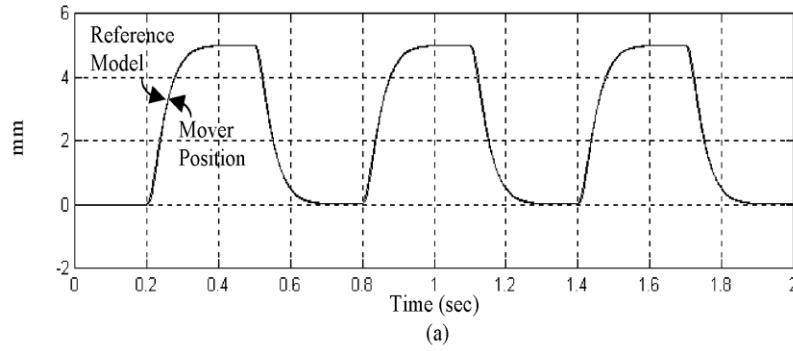


國立中央大學

## 位置控制器線上增益調整之控制系統(續)

### □模擬結果

標準動子質量



3倍動子質量

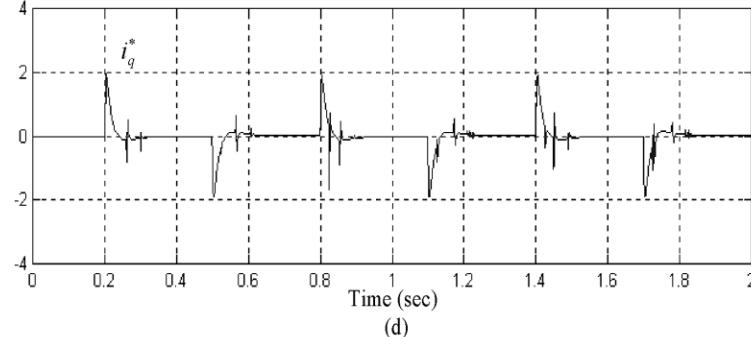
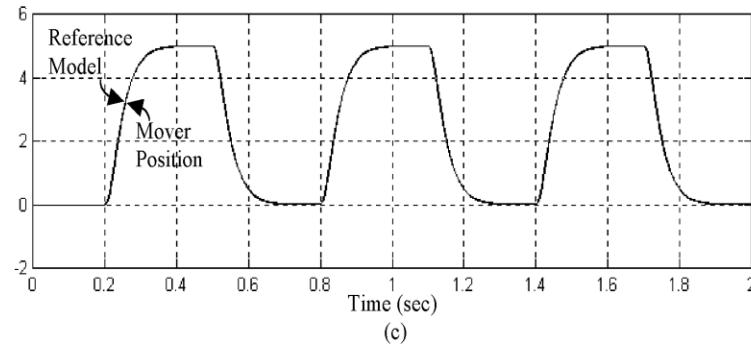


圖9.2

# 九、利用遞迴式模糊類神經網路於積分-比例

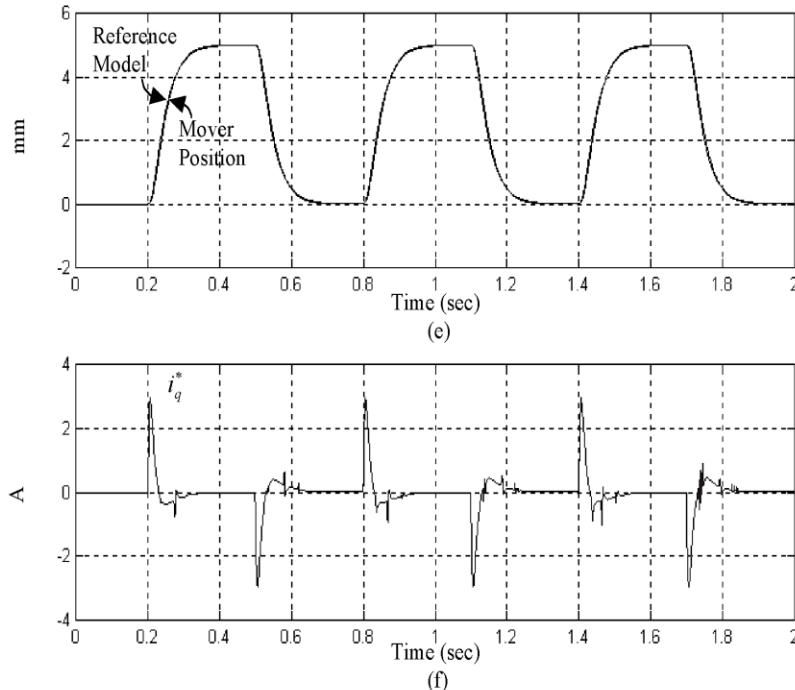


國立中央大學

## 位置控制器線上增益調整之控制系統(續)

### □模擬結果(續)

4.5 倍動子質量



0.4 秒加上負載

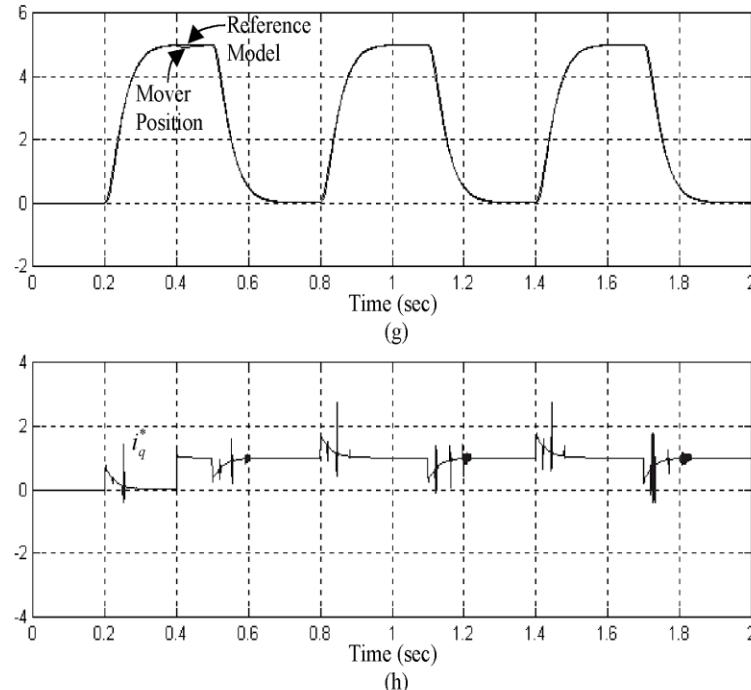


圖9.2(續)

# 九、利用遞迴式模糊類神經網路於積分-比例

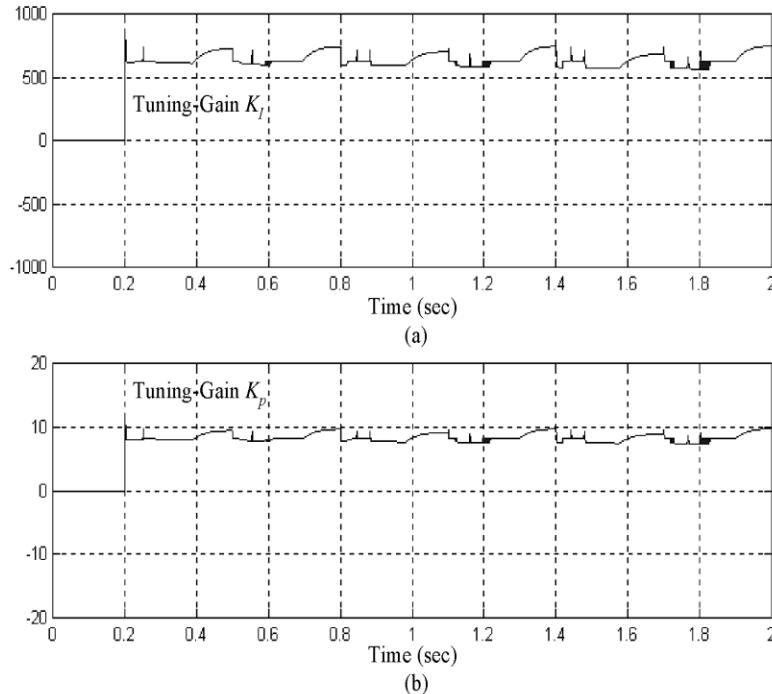


國立中央大學  
NCU NCU

## 位置控制器線上增益調整之控制系統(續)

### □模擬結果

標準動子質量



3 倍動子質量

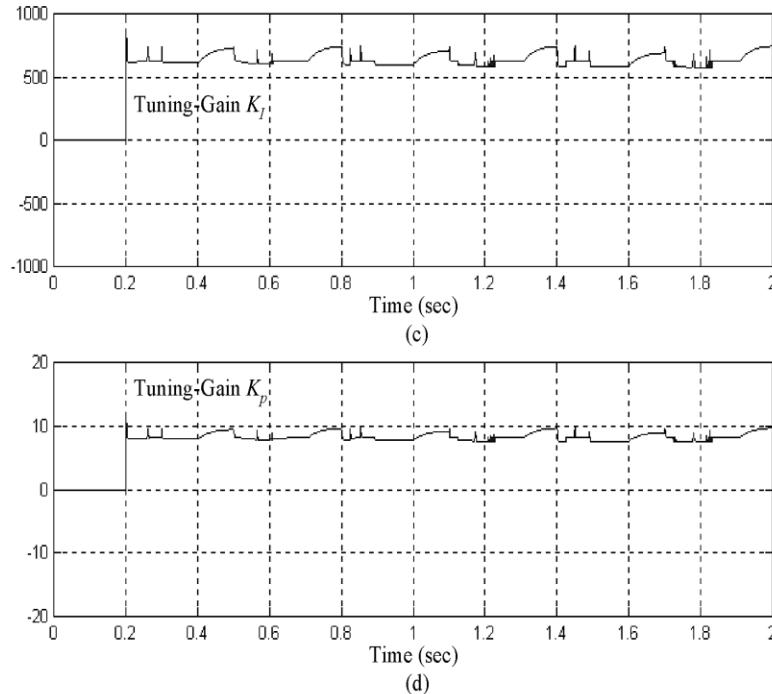


圖 9.3

# 九、利用遞迴式模糊類神經網路於積分-比例

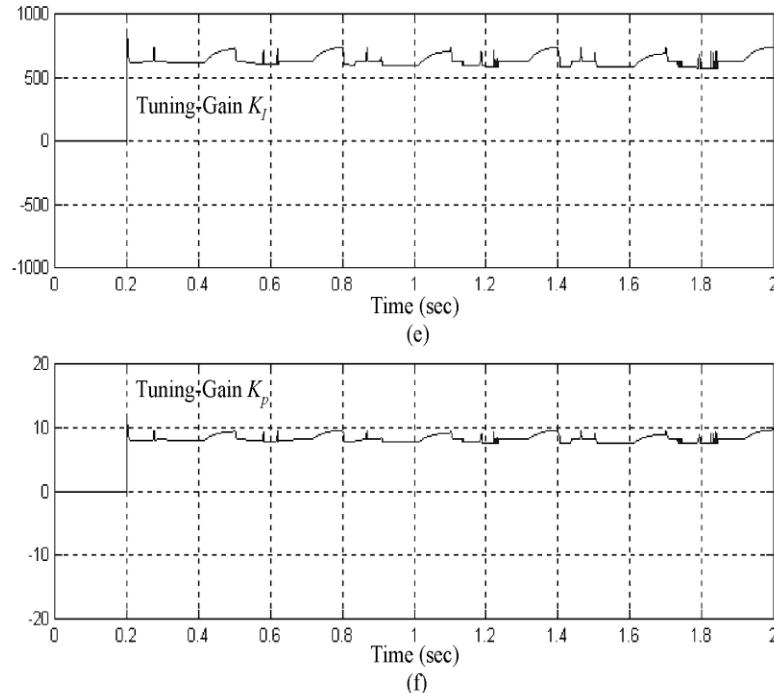


國立中央大學

## 位置控制器線上增益調整之控制系統(續)

### □模擬結果(續)

4.5 倍動子質量



0.4 秒加上負載

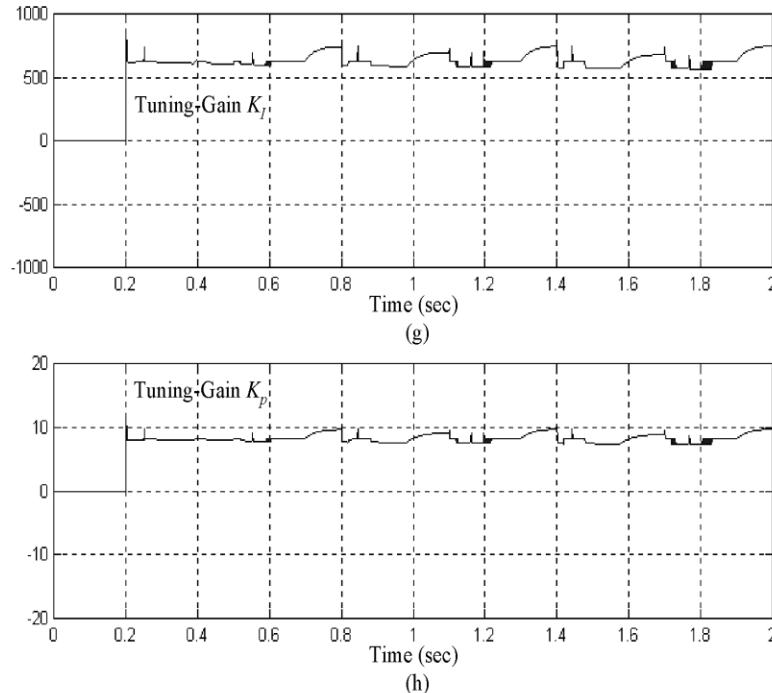
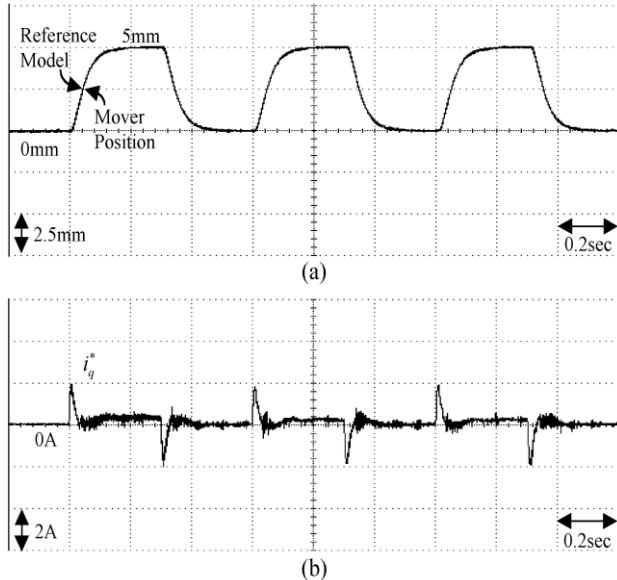


圖9.3(續)

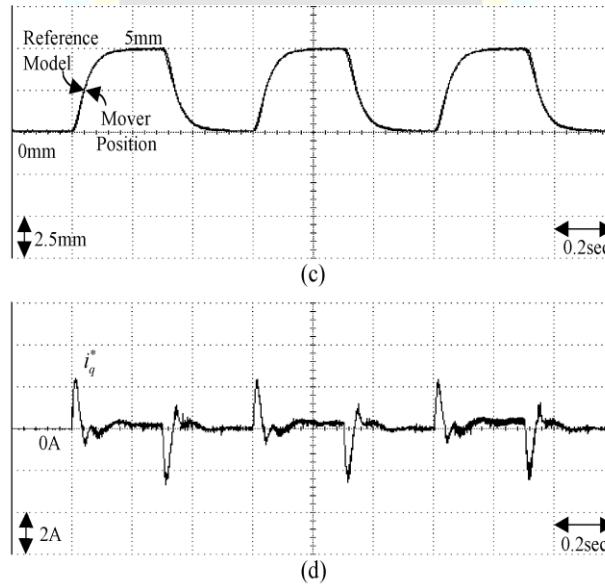
# 九、利用遞迴式模糊類神經網路於積分-比例

### □ 實測結果

標準動子質量



3倍動子質量



4.5倍動子質量

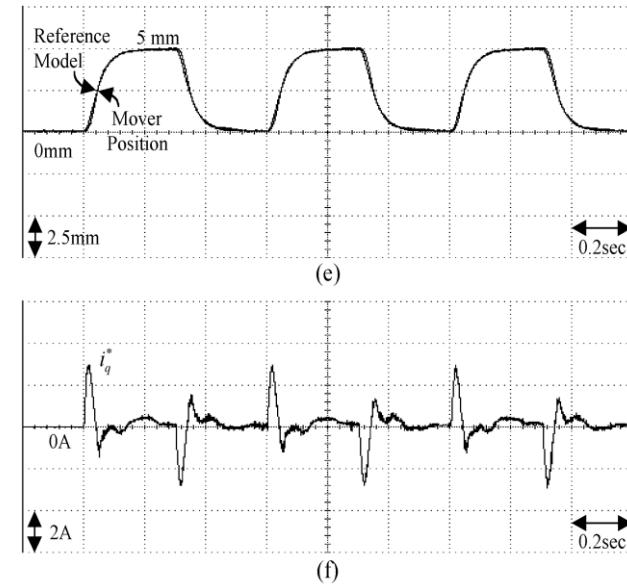


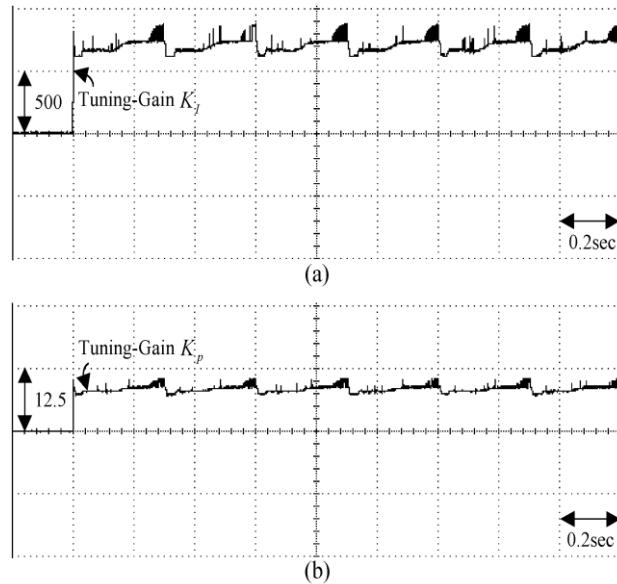
圖9.4

# 九、利用遞迴式模糊類神經網路於積分-比例

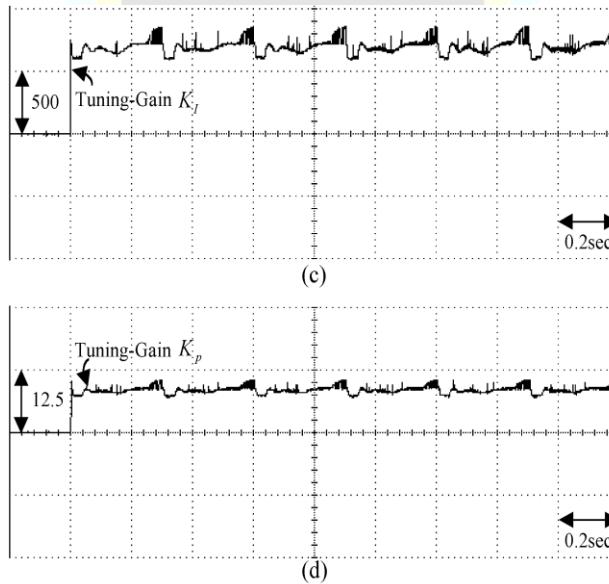
## 位置控制器線上增益調整之控制系統(續)

### □ 實測結果(續)

標準動子質量



3倍動子質量



4.5倍動子質量

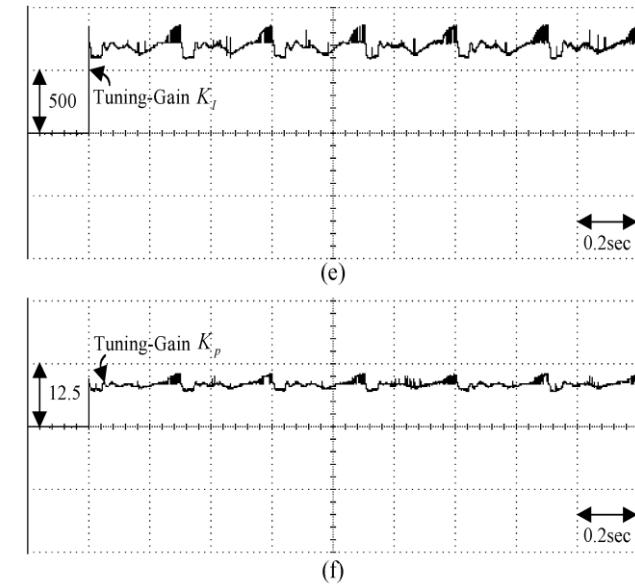


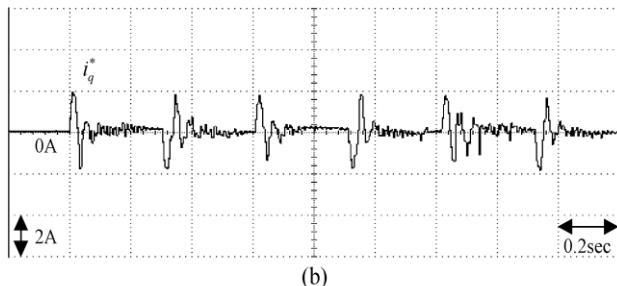
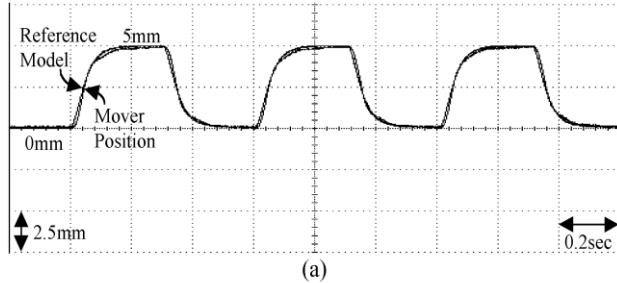
圖9.5

# 九、利用遞迴式模糊類神經網路於積分-比例

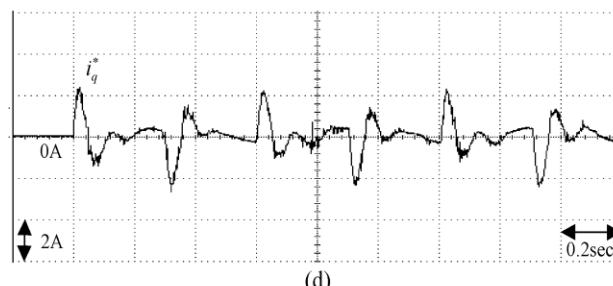
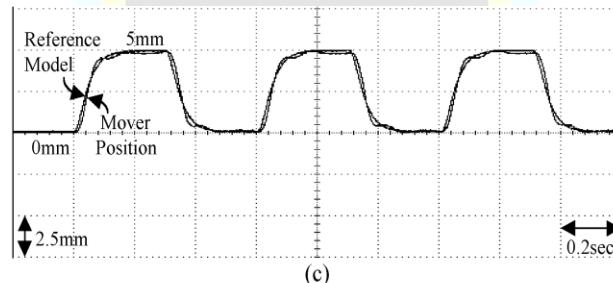
### □ 實測結果(續)

取樣時間為2毫秒

標準動子質量



3倍動子質量



4.5倍動子質量

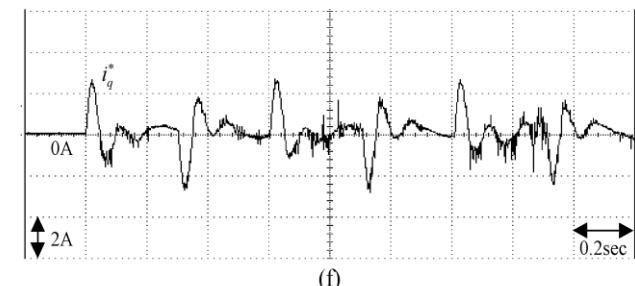
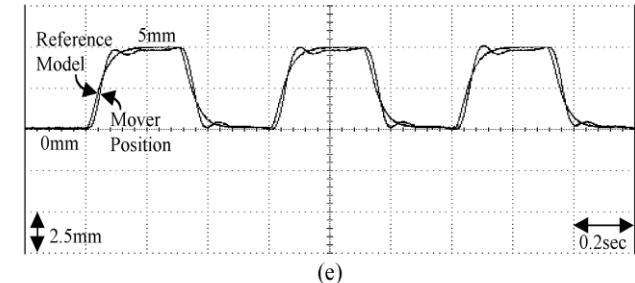


圖9.6

# 九、利用遞迴式模糊類神經網路於積分-比例



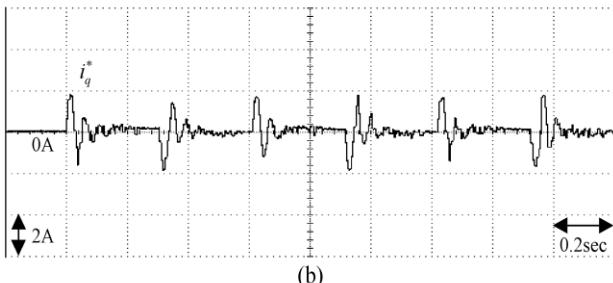
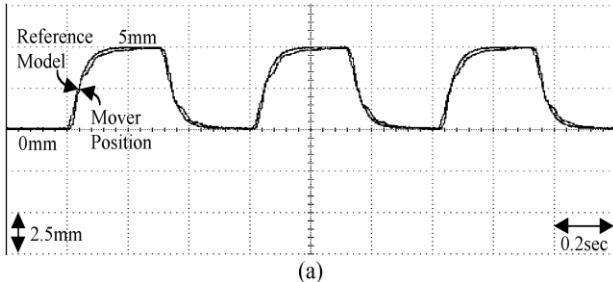
國立中央大學

## 位置控制器線上增益調整之控制系統(續)

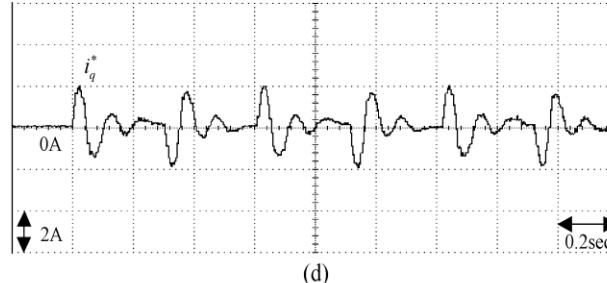
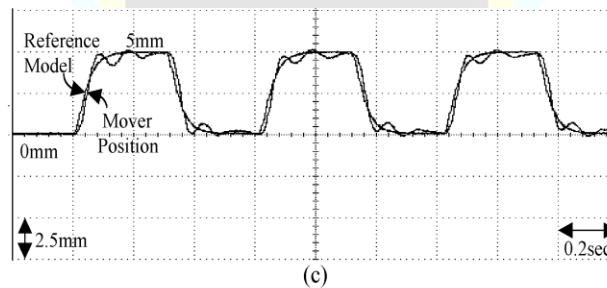
### □ 實測結果(續)

取樣時間為5毫秒

標準動子質量



3倍動子質量



4.5倍動子質量

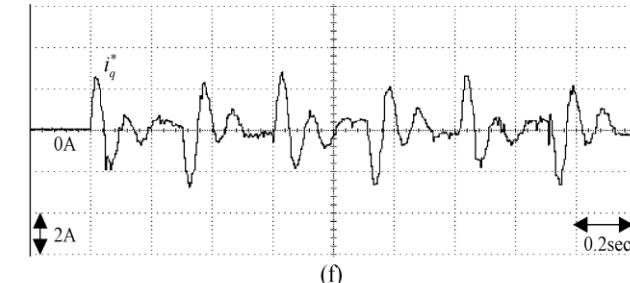
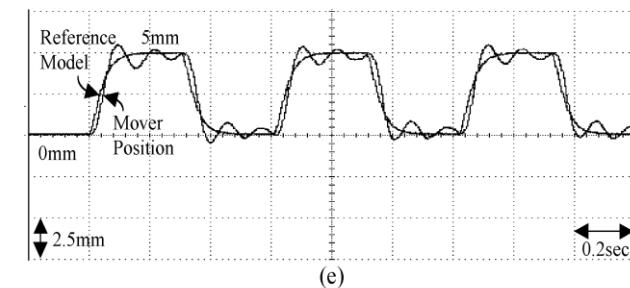


圖9.7



# 十、結論與未來的研究發展

- 個人電腦、伺服控制卡、向量處理器、電流控制脈寬調變之驅動電路、隔離電路與智慧型功率模組所完成的磁場導向控制永磁線型同步馬達驅動系統
- 提出四種不同的控制架構控制永磁線型同步馬達驅動系統，以實現強健與精密定位控制的目的
  - 遞迴式類神經網路補償器
  - 遞迴式類神經網路控制器
  - 以遞迴式類神經網路為基礎之適應混合型控制系統
  - 遞迴式模糊類神經網路為基礎於積分-比例位置控制器線上增益調整之控制系統



# 十、結論與未來的研究發展(續)

- 遲迴式類神經網路補償器主要應用於受控系統之未確定量過大時，將誤差經由遲迴式類神經網路產生補償訊號，以改善積分-比例位置控制器的追隨性能
- 遲迴式類神經網路控制器則應用於不同的週期性輸入命令，如步階命令或弦波命令，由於遲迴式類神經網路具有高度的適應性和學習能力，而且網路結合了前饋和迴授兩種連接方式，在動態行為和貯存資料方面皆具有良好的特性，故可使受控系統在不同週期性輸入命令時，具有強健控制的性能



# 十、結論與未來的研究發展(續)

- 為了補償最佳控制法則與遞迴式類神經網路之間的近似誤差，發展以遞迴式類神經網路為基礎之混合型控制系統和適應混合型控制系統的控制架構，以達到永磁線型同步馬達驅動系統之強健控制
- 提出一以遞迴式模糊類神經網路為基礎之積分-比例位置控制器線上增益的調整功能，改善系統受參數變化和外來負載干擾時所產生的影響，以增加強健控制特性



# 十、結論與未來的研究發展(續)

## □未來研究方向

- 由於輸出電壓與電流仍存在許多諧波成分，而驅動器電路易受電磁干擾的影響，並且智慧型功率模組內之 IGBT 於高切換時，會產生切換損失，加入命令波與三角波之同步脈寬調變技術、短路延遲時間的補償技術以及利用直流電源共振之零電壓切換技術，以降低干擾及損失，並提高驅動器的整體效率
- 在控制器之設計上，將  $H_\infty$  強健控制、類神經網路與其他非線性控制理論相結合之混合型控制架構，以實現高性能永磁線型同步馬達驅動系統