Bachelor Thesis

Studies on the Different Post-Processors and Building a Virtual Machining Environment for a 5-Axis Machine Tool.

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目錄

1. 緒論

1.1 概述

近年由於複雜的曲面加工以及縮短加工時間的需求增加，傳統三軸加工的加工誤差過大與加工時間過長之缺點讓多軸加工成為目前發展的趨勢，然而複雜的多軸加工又面臨著加工門檻過高的問題，如何以有效率且彈性的方法來降低加工門檻成了重要的議題，而快速且正確的建立加工前的處理和模擬也顯得更為重要。

目前大多數商用的 CAD/CAM 軟體如 UG NX, MASTERCAM 等, 只有內建的工具機機台做加工與碰撞之模擬，很難能夠建立新的機台來去做真實的碰撞預測，本文提出自行研發的軟體可以快速地建立不同工具機機台來做加工與碰撞的模擬，並可以以讀取通用的 CL 檔案來做特定機台的後處理得到真實工具機控制器可讀取的 NC 碼，以簡易的軟體輸入去預測碰撞、量測尺問，來降低多軸加工之門檻。

1.2 研究目的與方法

本文為提升多軸工具機加工前處理之速度與彈性，以讀取 UG NX 輸出的 CL 檔案，對特定機台，TMV 710A，做解析解後處理[1]，得到 SIEMENS 與新代 控制器可讀取之 NC 碼，並在 CL 檔案做插值來得到誤差較低的加工指令，最後使用國立成功大學李榮顯教授實驗室所研發的虛擬工具機加工環境自行建立虛擬工具機機台並模擬加工、碰撞和量測。

本文將以 NX 後處理建構器、梅可人之數值解後處理[2]以及數值解後處理所輸出之 NC 檔做比較，並比較在 CL 資料點間做插值數量對誤差影響的比較，以及用虛擬加工環境的碰撞功能去仿照三次元量床方法做加工後工件尺寸之量測。

2. 理論基礎與方法

2.1 建構虛擬工具機

2.1.1 CNC 工具機構型標準

CNC 工具機的軸向運動分為線性運動以及旋轉運動。線性運動為沿著參考軸做平行於參考軸之直線運動。旋轉運動則是繞著參考軸之旋轉。因此在各軸向、參考坐標有著統一的定義[3]，本文僅介紹立式銑床之定義。

工具機軸向為由右手定則決定(如圖 2-1a)，而根據機器運動指令的需求，習慣上用刀件相對於工件來定義。[4]立式工具機之 Z 軸定義為與旋轉主軸平行之軸，而工件與刀具距離增加之方向為 Z 軸的正方向。X 軸為垂直於 Z 軸並平行於最長行程，正方向為操作者正向工具機從轉軸往機柱看時，刀具往相對工件之右邊切削之方向，Y 軸為以右手定則與已決定好之 X、Z 來定義，如圖 2-2 中之 X’ 、Y’ 、Z’ ，其中 X’ 、Y’ 、Z’ 為移動工件之正方向，X、Y、Z 為刀具對工件之正方向。

三個旋轉軸為相對於 X、Y、Z 軸的旋轉軸，依序標示為 A、B、C，其中相對於 X 軸之旋轉軸為 A 軸；相對於 Y 軸之旋轉軸為 B 軸；相對於 Z 軸之旋轉軸為 C 軸，旋轉方向以右手定則做定義，大拇指為 X、Y、Z 之正方向，其他四根手指螺旋之方向即為旋轉正方向(如圖 2-1b)。

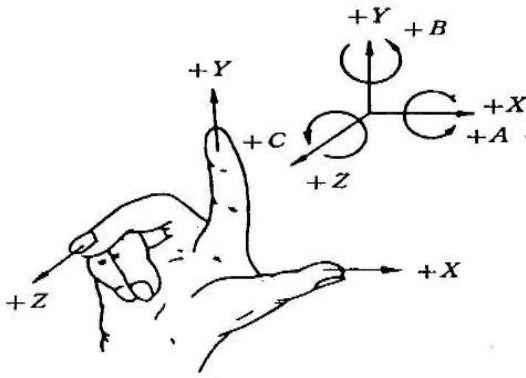


圖 2-1a

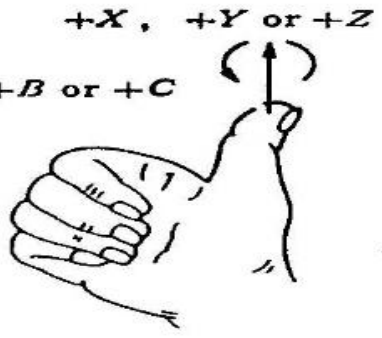


圖 2-1b

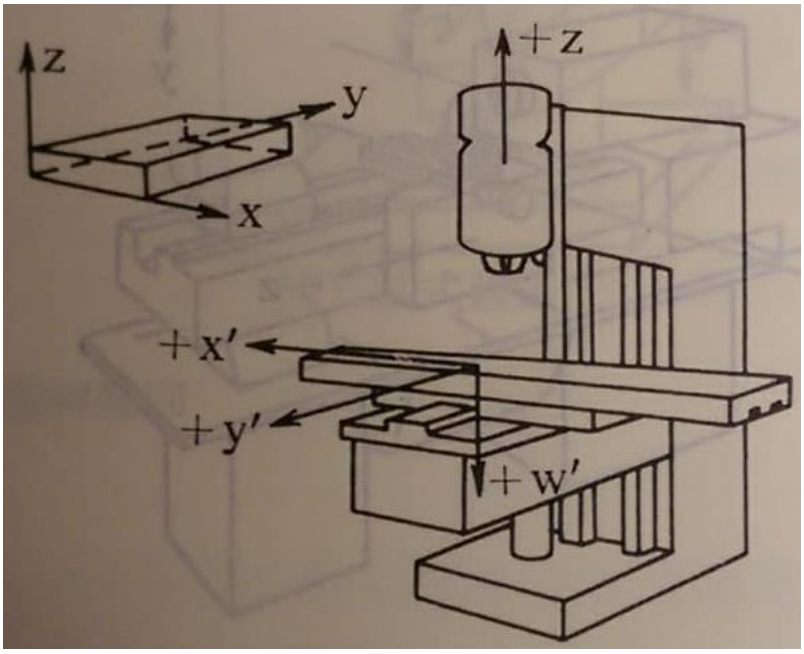


圖 2-2

2.1.2 虛擬工具機構型之組裝

國立成功大學李榮顯教授實驗室所開發之虛擬工具機環境中，機台構型是用機台樹狀圖來做組裝，本文以東台精機股份有限公司所開發的 TMV-710A 立式五軸工具機(A、C 軸工作檯傾斜型)之簡易構型為範例。首先須先觀察機台底座以及各軸之關聯，其中分為底座(Base)、X 軸機構、Y 軸機構、Z 軸機構、主軸(Spindle)五個部分，來繪製樹狀圖(圖 2-3)此虛擬工具機為根據機台廠商之工程圖所建構。

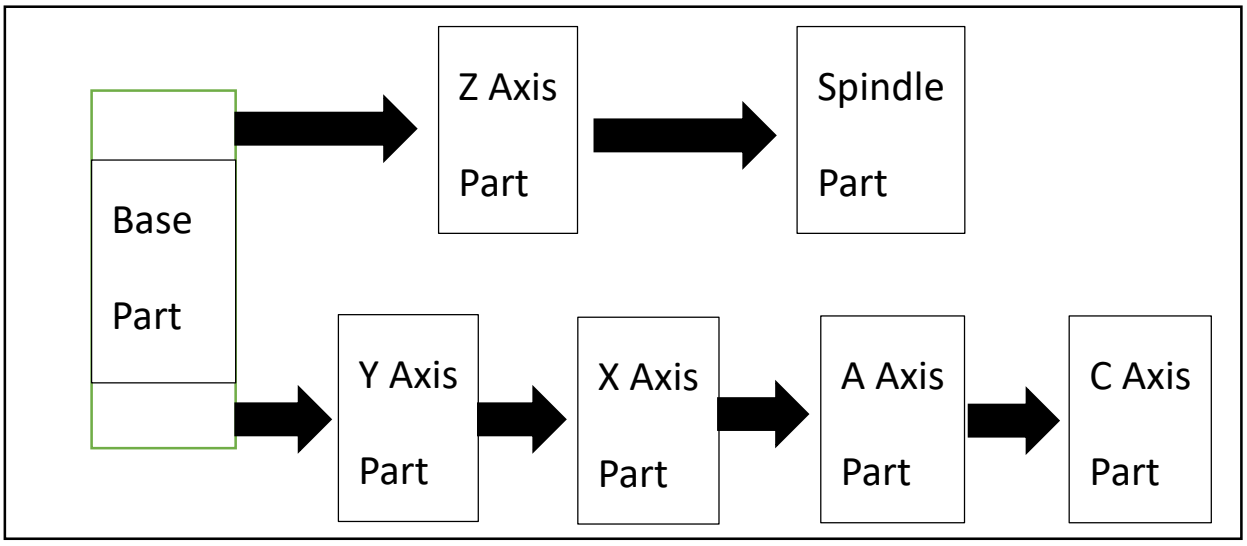


圖 2-3

各部位 STL 檔案經過虛擬工具機環境處理各個相對位置後，虛擬機台如圖 2-4 所示，其中各軸之定義方向即為如 2.1.1 章所介紹。

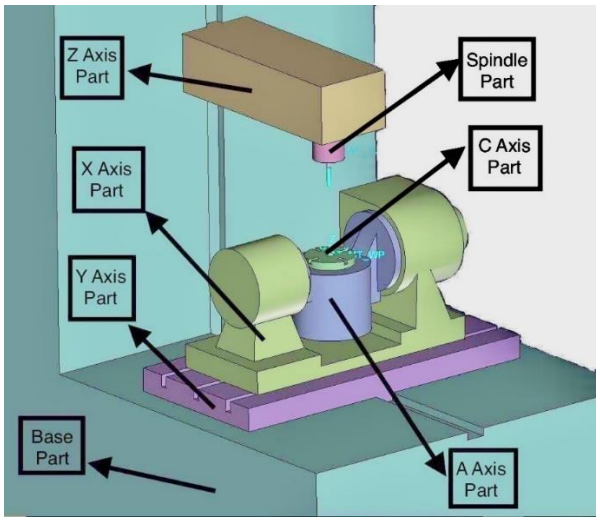


圖 2-4

2.2 後處理方法

2.2.1 後處理概述

如圖 2-5，後處理為電腦輔助製造程式設計與製造間重要的橋梁，後處理程式將通用的刀具位置(CL 檔)轉換為特定機台的加工操作資料，如此 CNC 工具機讀取這些資料後，就能依照程式加工。由於五軸工具機的種類繁多，加上各家控制器製造廠家有著不同的控制碼定義，因此五軸後處理程式通常都是個別獨立處理，即每部五軸工具機都有其專用的後處理，也因為五軸加工機具有多軸同動洗削功能，軟體所需定義的相關參數甚多，對於初次使用者而言，除非具有相當的工具機使用經驗以及學理基礎，否則往往不能定義出真實的工具機參數，也可能因此造成精密的多軸工具機損壞，所以可知準確後處理的重要性，本文將依照 TMV-710A AC 五軸加工機所搭配之新代控制器來做後處理，所探討的後處理也只針對刀具座標控制點轉作作處理。

圖 2

2.2.2 數值解後處理流程

數值分析方法指對數學問題用遞迴趨近來得到近似解，本文數值解參考梅可人[2]使用 Broyden 方法之程式，每一行 CL 皆須一 NC 作為趨近之起動值，針對第一行的 CL，以機械原點之 NC 趨近。對每一行 CL，以上一行之 CL 相對應之 NC 趨近。若趨近失敗，則將上一次趨近之 CL 與當下欲趨近之 CL 做插值，再以插值所得之 CL 做趨近。若趨近成功，則對下一個未處理之 CL 進行如上之趨近劉程；若趨近成功且該 CL 為使用者輸入之 CL 檔案，則將其 NC 紀錄並對下一個未處理之 CL 進行如上所述之趨近，如圖 2-5。

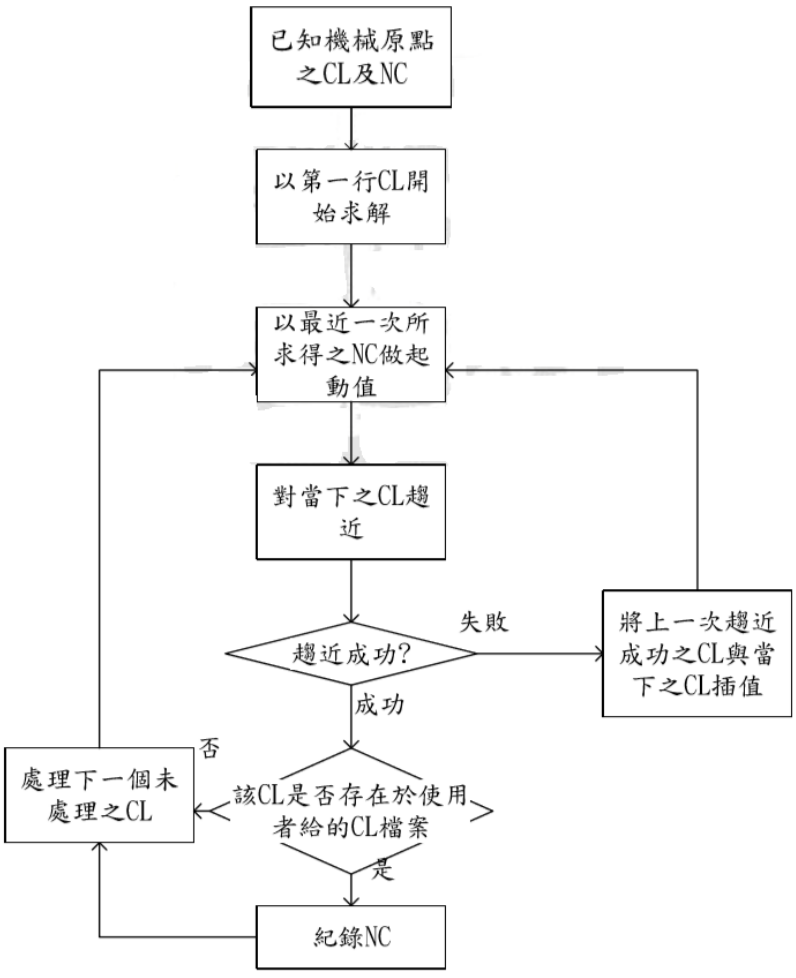


圖 2-5

2.2.3 五軸加工之幾何定義

一般五軸加工的刀具位置資料包含描述工件坐標系$O_W X_W Y_W Z_W$中，刀具中心尖端的座標$\tilde{Q}$以及刀軸方向$\tilde{K}$(如圖 2-6)，以矩陣的型式表示如下：

$$\begin{bmatrix} \tilde{\mathbf{K}} & \tilde{\mathbf{Q}} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} K_x & Q_x \\ K_y & Q_y \\ K_z & Q_z \\ 0 & 1 \end{bmatrix} \quad (2\text{-}1)$$

其中K_x、K_y、K_z為向量$\tilde{K}$之方向餘弦；Q_x、Q_y、Q_z為位置座標$\tilde{Q}$的三個座標分量，此處注意向量$\tilde{K}$皆為從工件指向外的方向。

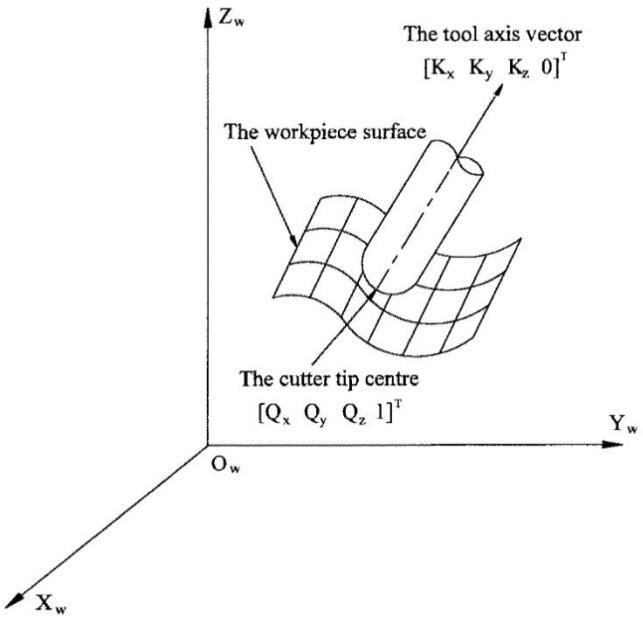


圖 2-6

2.2.4 解析解公式推導

解析解後處理的推導源自於逆向運動學，也就是已知末端點(刀尖)位置，來求得各軸的位置移動以及轉動角度，而逆向運動學所用到的運動齊次座標轉換矩陣如下公式(1)～(4)。(1)代表對 X 軸移動 a、Y 軸移動 b、Z 軸移動 c，(2)代表對 X 軸轉θ角度，(3)代表對 Y 軸轉θ角度，(4)代表對 Z 軸轉θ角度。座標之轉換可以經由矩陣前乘來對原有坐標系座移動或旋轉。

$$\mathbf{Trans}(a,b,c)=\begin{bmatrix}1&0&0&a\\0&1&0&b\\0&0&1&c\\0&0&0&1\end{bmatrix} \quad (1)$$

$$\mathbf{Rot}(X,\theta)=\begin{bmatrix}1&0&0&0\\0&C\theta&-S\theta&0\\0&S\theta&C\theta&0\\0&0&0&1\end{bmatrix} \quad (2)$$

$$\mathbf{Rot}(Y,\theta)=\begin{bmatrix}C\theta&0&S\theta&0\\0&1&0&0\\-S\theta&0&C\theta&0\\0&0&0&1\end{bmatrix} \quad (3)$$

$$\mathbf{Rot}(Z,\theta)=\begin{bmatrix}C\theta&-S\theta&0&0\\S\theta&C\theta&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix} \quad (4)$$

本文僅討問 AC 軸工作台傾斜型工具機，如圖 2-7，在工作台上有兩個迴轉軸，假設兩旋轉軸相交於軸心點 R。圖 2-8 中坐標系$O_WX_WY_WZ_W$及$O_tX_tY_tZ_t$分別為工件及刀尖座標系統，而向量$L_x\boldsymbol{i}+L_y\boldsymbol{j}+L_z\boldsymbol{k}$為工件原點$O_W$至 R 點之偏移向量，此偏移向量代表實際工件架設在工具機上時，工件原點與旋轉軸心點的相對位移。

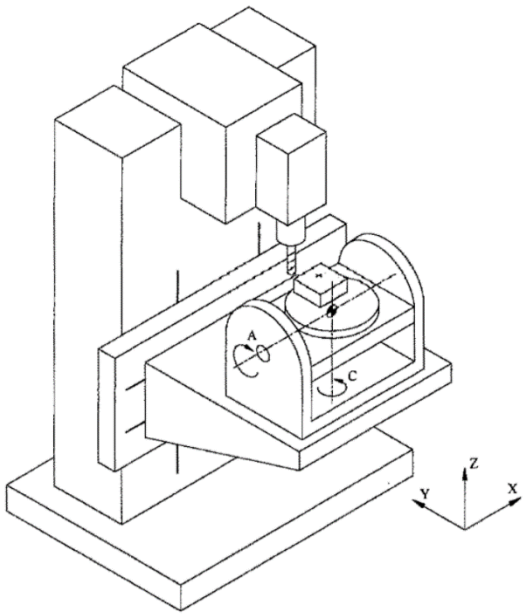


圖 2-7

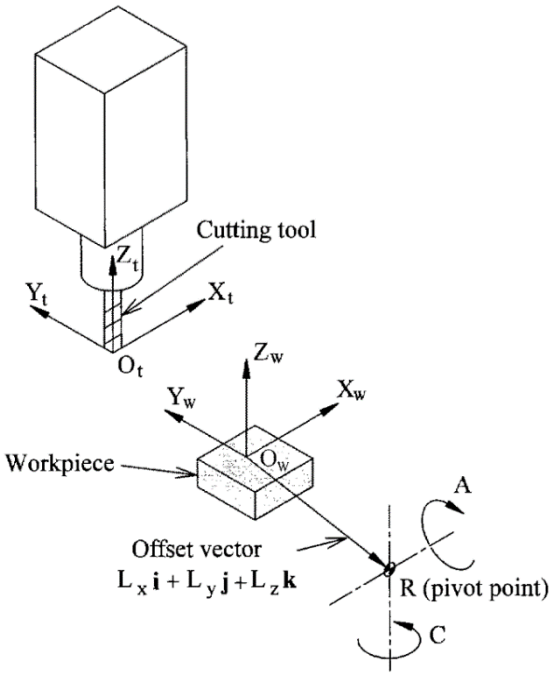


圖 2-8

由於此類型工具機實際的機構元件包含了旋轉台、線性平台、床台、主軸頭、刀具，因此可以由工件座標系開始，利用一連串的齊次座標轉換至刀具座標系，便可以得到其形狀創成函數矩陣，其轉換流程如圖 2-9 所示，以數學的表達如下：

$$\text{Trans}(L_x,L_y,L_z)\times\text{Rot}(z,\varphi_z)\times\text{Rot}(x,\varphi_x)\times\text{Trans}(P_x,P_y,P_z)\times\begin{bmatrix}0&0\\0&0\\1&0\\0&1\end{bmatrix} \quad (2\text{-}2)$$

其中φ_x及φ_y為旋轉台繞著 X 軸及 Z 軸之旋轉角度，而正方向旋轉角式沿著+X 及+Z 軸右手螺旋方向。P_x、P_y、P_z為線性平台相對於 X、Y、Z 軸之相對位移。(2-1)式為圖 2-7 構型工具機的形狀創成函數矩陣，說明工件與刀尖的相對位置和方位。對於一個已知的刀尖路徑資料，可令(2-2)式與(2-1)式相等，解出所需的工具機參數。

將(2-2)式展開，並令其與(2-1)相等，可得：

$$\begin{bmatrix}K_x&Q_x\\K_y&Q_y\\K_z&Q_z\\0&1\end{bmatrix}=\begin{bmatrix}S\varphi_xS\varphi_z & L_x+P_xC\varphi_z-P_yC\varphi_xS\varphi_z+P_zS\varphi_xS\varphi_z\\ -S\varphi_xC\varphi_z & L_y+P_xS\varphi_z+P_yC\varphi_xC\varphi_z-P_zS\varphi_xC\varphi_z\\ C\varphi_x & L_z+P_yS\varphi_x+P_zC\varphi_x\\ 0 & 1\end{bmatrix} \quad (2\text{-}3)$$

比較(2-3)式左右兩邊所對應的第 1 行及第 2 行元素，可分別得到 6 組聯立

方程式，以解得未知數φ_x、φ_z及P_x、P_y、P_z。其求解的過程是先解出旋轉角φ_x、φ_z，再解出相對位移P_x、P_y、P_z值。取(2-3)式左右兩邊的第一行，雖然未知數只有φ_x、φ_z，卻有 3 組聯立方程式，但因K_x、K_y、K_z有$K_x + K_y + K_z = 1$之關係，因此實際上只有 2 組獨立的聯立方程式。

由(2-3)式左右兩邊的第一行，可以解出φ_x、φ_z之值如下：

$$\varphi_x = arcos(K_z) \qquad 0 \le \varphi_x \le \pi \qquad (2\text{-}4)$$
$$\varphi_z = arctan2(K_x, K_z) \qquad -\pi \le \varphi_z \le \pi \qquad (2\text{-}5)$$

其中$arctan2$為特殊函數，可依 x、y 座標值回應角度值再$[-\pi,\pi]$之值域中，其定義為

$$\theta = \begin{cases} 0 \le \theta \le \dfrac{\pi}{2} & \text{for } x \ge 0 \text{ and } y \ge 0 \\ \dfrac{\pi}{2} \le \theta \le \pi & \text{for } x \le 0 \text{ and } y \ge 0 \\ -\pi \le \theta \le -\dfrac{\pi}{2} & \text{for } x \le 0 \text{ and } y \le 0 \\ -\dfrac{\pi}{2} \le \theta \le \pi & \text{for } x \ge 0 \text{ and } y \le 0 \end{cases}$$

要注意的(2-4)式中，由於 arcos 的值域$[0,\pi]$，限制了φ_x角的範圍，若是φ_x角在$[-\pi,0]$範圍中，則φ_x及φ_z之解應修正為：

$$\varphi_x = -arcos(K_z) \qquad -\pi \le \varphi_x \le 0 \qquad (2\text{-}4)$$
$$\varphi_z = arctan2(-K_x, -K_z) \qquad -\pi \le \varphi_z \le \pi \qquad (2\text{-}5)$$

再來由(2-3)式左右兩邊的第二行可以解出P_x、P_y、P_z之值如下：

$$P_x = (Q_x - L_x)\mathrm{C}\varphi_z + (Q_y - L_y)\mathrm{S}\varphi_z \qquad (2\text{-}6)$$
$$P_y = -(Q_x - L_x)\mathrm{C}\varphi_x\mathrm{S}\varphi_z + (Q_y - L_y)\mathrm{C}\varphi_x\mathrm{C}\varphi_z + (Q_z - L_z)\mathrm{S}\varphi_x \qquad (2\text{-}7)$$
$$P_z = (Q_x - L_x)\mathrm{S}\varphi_x\mathrm{S}\varphi_z - (Q_y - L_y)\mathrm{S}\varphi_x\mathrm{C}\varphi_z - (Q_z - L_z)\mathrm{C}\varphi_x \qquad (2\text{-}8)$$

此處所解得的P_x、P_y、P_z，並不式真實的 X、Y、Z 軸 NC 碼，一般而言，NC 加工所對應的各軸運動，必須相對於一個程式座標系，這個座標細在不同的控制器則利用不同的 G 碼來設定，以 SYNTEC 控制器而言，使用 G54 至 G59.9 一共 15 個座標系定義程式原點，而大部分的情況程式原點與刀尖路徑資料的工件座標系原點重合。因此假設程式原點與工件原點重合，此時可利用(2-3)式左右兩邊的第二行，當$\varphi_x = \varphi_z = 0$時，

$[Q_x \quad Q_y \quad Q_z \quad 1]^T = [L_x + P_x \quad L_y + P_y \quad L_z + P_z \quad 1]^T$，化簡得：
$[\mathrm{X} \quad \mathrm{Y} \quad Z \quad 1]^T = [L_x + P_x \quad L_y + P_y \quad L_z + P_z \quad 1]^T$

因此本構型之五軸 NC 碼參數方程式為：

$$\mathrm{A}=\varphi_x=\begin{cases} arcos(K_z) & 0 \le \varphi_x \le \pi \\ -arcos(K_z) & -\pi \le \varphi_x \le 0 \end{cases}$$

$$\mathrm{C}=\varphi_z = arctan2(K_x sign(\mathrm{S}\varphi_x), K_z sign(\mathrm{S}\varphi_x)) \qquad -\pi \le \varphi_z \le \pi$$

$$\text{其中 } \mathrm{sign}(\mathrm{S}\varphi_x)=\begin{cases} 1 & \text{當 } \mathrm{S}\varphi_x \ge 0 \\ -1 & \text{其他} \end{cases}$$

$$\mathrm{X}=L_x + P_x = (Q_x - L_x)\mathrm{C}\varphi_z + (Q_y - L_y)\mathrm{S}\varphi_z + L_x$$
$$\mathrm{Y}=L_y + P_y = -(Q_x - L_x)\mathrm{C}\varphi_x\mathrm{S}\varphi_z + (Q_y - L_y)\mathrm{C}\varphi_x\mathrm{C}\varphi_z + (Q_z - L_z)\mathrm{S}\varphi_x + L_y$$
$$\mathrm{Z}=L_z + P_z = (Q_x - L_x)\mathrm{S}\varphi_x\mathrm{S}\varphi_z - (Q_y - L_y)\mathrm{S}\varphi_x\mathrm{C}\varphi_z - (Q_z - L_z)\mathrm{C}\varphi_x + L_z$$

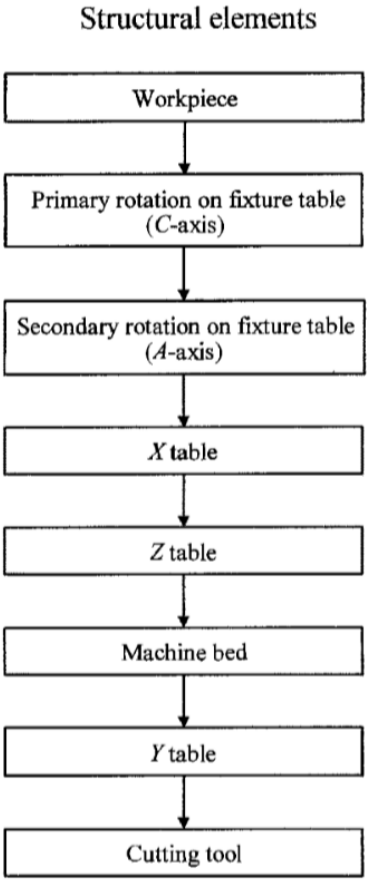


圖 2-9

2.2.5 解析解後處理程式流程

利用 CAD/CAM 軟體所輸出的 CL 檔(刀尖位置)，再分別用$[-\pi,0]$和$[0,\pi]$兩個值域的後處理公式得到兩組 NC 碼，選擇第一行 NC 碼 C 軸需旋轉最小的 NC 碼組並紀錄之，因為兩組 NC 碼是相同 CL 檔的對偶根，加上為使加工過程刀具路徑連續，每行 NC 碼必須在兩組 NC 碼中做選擇，吾人使用選擇新的 X 軸數值與上一行 X 軸數值相差較小來繼續流程，以維持加工之連續性。如下圖

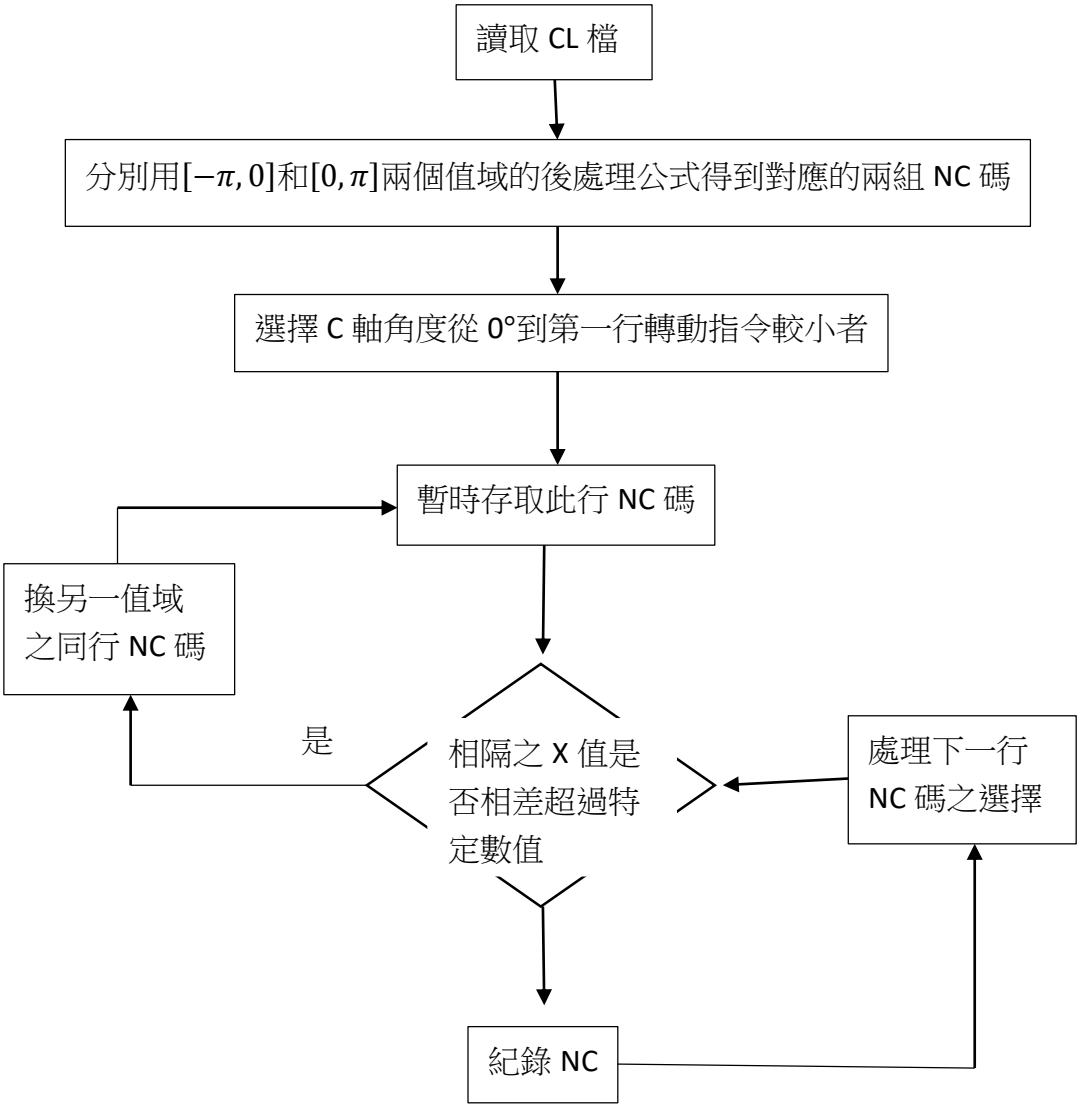


圖 2-10

2.3 插值目的與方法

CL 檔案為使用許多的 GOTO 指令(如圖 2-11)，也就是許多的直線小線段去趨近加工曲線路徑，在 NC 碼中為使用許多的 G01 線段做曲線的趨近。在 CL 檔案中 GOTO 後的前三個值為相對工件原點給定刀尖位置的 X、Y、Z 座標，兩個 GOTO 點座標間刀尖是以線性平均來移動到下一個 GOTO 目標座標，然後 NC 碼為各軸 G01 值的平均來做兩個 G01 值之間的移動，因此在三軸加工時，由於只有線性平台之位移，所以 CL 檔中 GOTO 間平均的移動與 NC 碼之 G01 間各軸的平均移動是等效的。然而在五軸加工，因為多了旋轉軸之指令，NC 碼之 G01 間各軸的平均移動和旋轉經過逆向後處理得到的 CL 檔，並不會等同於原先的 CL 檔指令，也就是說後處理得到的 NC 碼只有在 G01 給定的點時才會是在真實加工路徑上，G01 點間的路徑並不會等於所要求的加工路徑。

```
GOTO/45.1072,-50.0003,23.4884,-0.2745937,-0.2881959,0.9173557
GOTO/40.1766,-50.0000,22.1062,-0.2374081,-0.2911482,0.9267525
GOTO/37.6874,-50.0000,21.5064,-0.2096495,-0.2930564,0.9328263
```

圖 2-11

為解決此問題，可以將 CL 檔先做插值，再將插值出來各點做後處理得到更符合要求之加工路徑的 NC 碼。插值的方法有許多種，像是線性插值、一次方程插值與多次方程插值，而本文使用線性插值來做測試。

假設有兩點 a、b，其座標為(X_a, Y_a, Z_a)、(X_b, Y_a, Z_a)，若想對其兩點間做 n 個插值，其各點之位置座標為

$$X_{a,i} = X_a + \frac{X_b - X_a}{n+1} \times i \qquad (i = 1 \sim n+1)$$

$$Y_{a,i} = Y_a + \frac{Y_b - Y_a}{n+1} \times i \qquad (i = 1 \sim n+1)$$

$$Z_{a,i} = Z_a + \frac{Z_b - Z_a}{n+1} \times i \qquad (i = 1 \sim n+1)$$

而要做多少個插值，就以所需的誤差來做決定，在本文後也將討論之。

另外，為解決五軸加工機插值的不便，除了使用參數式曲線之趨近，大部分控制器廠商在工具機控制器裡有個 G43.4，刀尖點控制功能，Rotational Tool Center Point(RTCP)的指令，以新代控制器為例，在一般機台上，控制器的移動命令是下給刀柄或者主軸鼻端，開啟刀尖點控制後，移動命令會改以刀尖點所在座標來作控制，此功能是五軸加工機特有之功能。如下圖 2-12 中有兩條加工軌跡，橘色軌跡是一般加工狀況的機台路徑，控制器控制主軸鼻端的軌

跡，因此與工件表面會相差一個刀長；藍色軌跡則是 RTCP 開啟時，控制器控制刀尖點的路徑，在產出加工程式時，直接描述工件表面的座標，這樣的加工程式，可以忽略刀長的變化，以及機台之間的機構差異，可以讓程式更有效率的被使用，也可以避免上述插值的問題，圖 2-13 為 RTCP 之使用範例，未開啟 RTCP 前，直線軸與旋轉軸的動作各自獨立，開啟 RTCP 後，刀尖點的線性移動命令優先，旋轉軸需配合刀尖點來進行轉動。

圖 2-12

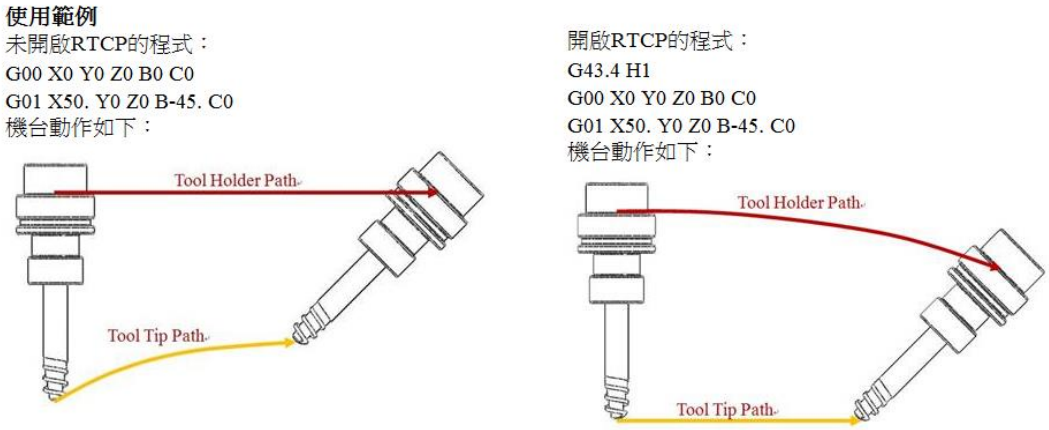


圖 2-13

3. 結果與討論

3.1 數值解與解析解比較

本文以東台精機股份有限公司所開發的 TMV-710A 立式五軸工具機(A、C 軸工作檯傾斜型)之構型來建構虛擬工具機，本構型在圖 2-8 的L_x、L_y、L_z為(0、0、-20)，經過 2.2.5 章之解析解後處理流程得到的 NC 碼，與該構型在 NX 軟體中對該構型後處理之 NC 碼，以及 2.2.2 章數值解得到的 NC 碼來做比較與驗證。

吾人用 Solidworks 建構一個前基準面為一個正弦方塊對右基準面另一個正弦函數做曲線拉伸的加工件，如圖 3-1

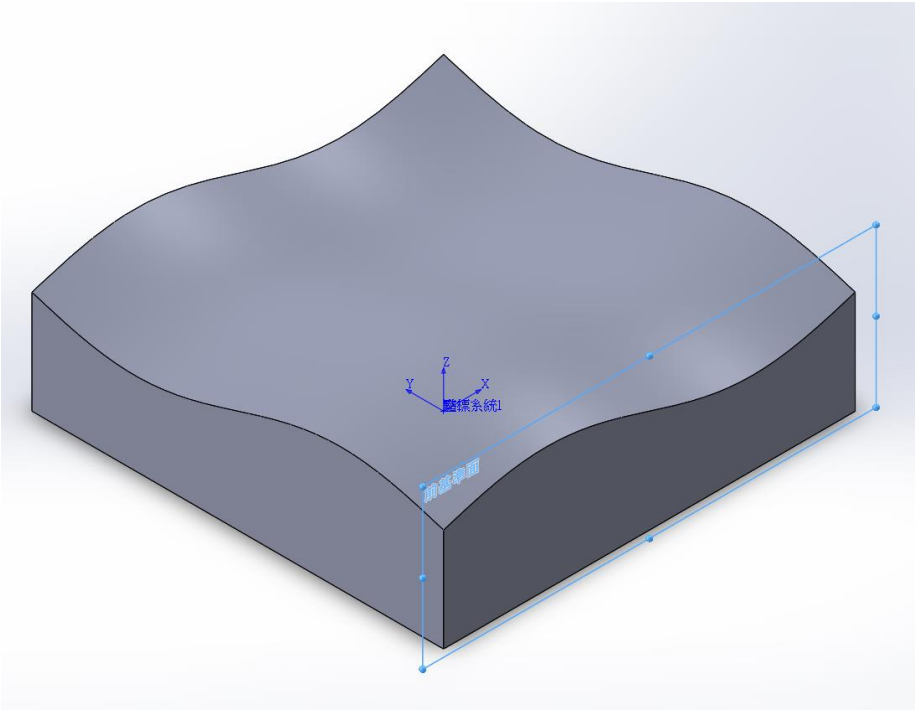


圖 3-1

其中 x 方向之正弦函數為 $z = 20 + 5\sin(\frac{2\pi x}{100})$

y 方向之正弦函數為 $z = 20 + 5\sin(\frac{2\pi y}{100})$

因此 3D 之曲面高度方程式為 $z=20 + 5\sin(\frac{2\pi x}{100})+5\sin(\frac{2\pi y}{100})$

因此只要知道 x、y 的值就可以知道 z 與該點的法向量。

將此加工件匯入 NX 去可設定要求之家工路徑以求 CL 檔與 TMV-710A 此構型之 NC 碼，這裡吾人使用刀軸垂直於驅動體此功能來用曲面之法向量作為加工路徑刀軸之向量，如圖 3-2。

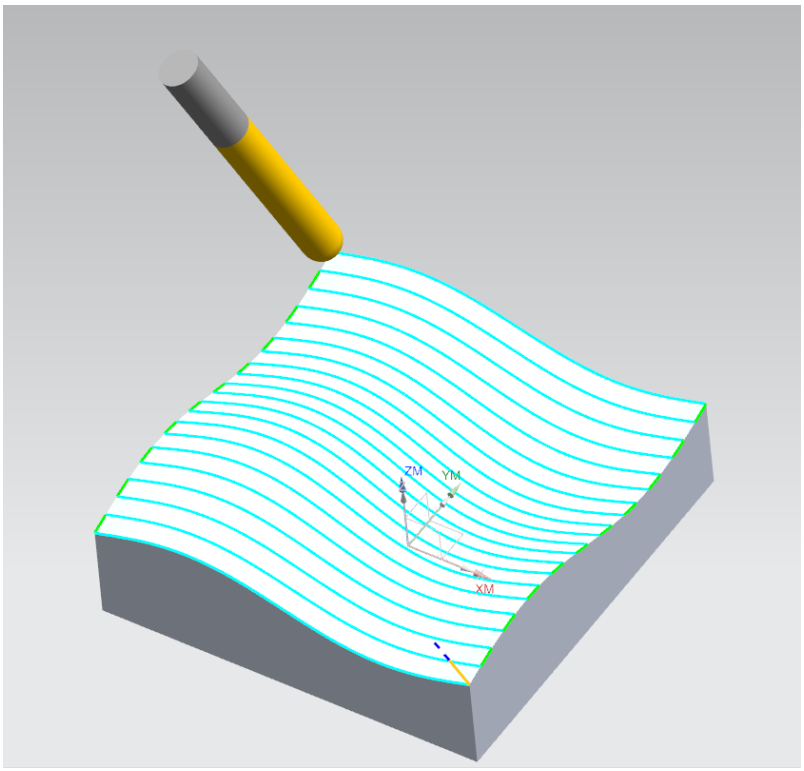


圖 3-2

而本文只探討前三條加工路徑，其完整的 CL 檔、NX 輸出之 NC 檔、本文使用之解析解後處理輸出之 NC 檔以及數值解後處理輸出之 NC 檔將放在附錄以便參考。

以 CL 檔案中的前四行來做比較

```
GOTO/50.0000,-50.0000,25.0000
GOTO/45.1072,-50.0003,23.4884,-0.2745937,-0.2881959,0.9173557
GOTO/40.1766,-50.0000,22.1062,-0.2374081,-0.2911482,0.9267525
GOTO/37.6874,-50.0000,21.5064,-0.2096495,-0.2930564,0.9328263
```

圖 3-3

解析解 NC 碼

```
X70.710678    Y18.270869    Z21.123902    A23.955018    C315.
X67.147925    Y12.647645    Z21.91806     A23.457486    C316.384526
X62.734816    Y3.436297     Z24.041184    A22.065882    C320.805505
X59.743114    Y-2.523146    Z25.46994     A21.120241    C324.420464
```

圖 3-4

數值解 NC 碼

```
x: 70.71068    y: 18.18607    z: -153.83853  a: 23.83692    c: -45.
x: 67.1699     y: 12.9861     z: -153.22086  a: 23.54542    c: -43.87059
x: 62.82324    y: 3.91087     z: -151.12475  a: 22.17472    c: -39.57977
x: 59.77278    y: -2.41825    z: -149.56336  a: 21.14094    c: -35.67048
```

圖 3-5

NX 後處理 NC 碼

X70.711	Y18.271	Z21.124	A23.955	C315.
X67.148	Y12.648	Z21.918	A23.457	C316.385
X62.735	Y3.436	Z24.041	A22.066	C320.806
X59.743	Y-2.523	Z25.47	A21.12	C324.42

圖 3-6

以上之比較可以發現 NX 之後處理與解析解之後處理的 NC 碼一致，故可猜測 NX 為使用解析解後處理的方式來處理 NC 碼。值得注意的是，數值解得到的 NC 碼雖然與解析解以及 NX 之 NC 檔不同，但真正需要比較的為該 NC 碼命令機台移動後，刀尖相對於工件之位置，以及刀軸之方向，所以經由同方法之逆向後處理可以得知該 NC 碼所對應的 CL 檔(如圖 3-7)，與後處理前之 CL 檔(圖 3-3)誤差極小，因此該數值解仍為可行之後處理方法。

(49.99999999998,-50.0000000000,25.000000000035),(-0.28576646524543,-0.2857664652454,0.9146994340669)

(45.10719999999,-50.00029999999,23.488400000002),(-0.2768495838193906,-0.2879850218105,0.9167436583647)

(40.176599999988,-49.9999999999995,22.106199999989),(-0.24048162071514,-0.29090140070708,0.9260372374613)

(37.68739999998,-50.00000000002,21.506400000006),(-0.21031104607895,-0.29299720449116,0.9326960394778)

圖 3-7

3.2 不同插值對誤差的比較

本章的比較也是由同上一章所使用之加工件與加工方法(圖 3-2)，比較方法為將每段 CL 檔做 N 個插值，轉為 NC 檔後將相鄰兩點 NC 檔做平均得到一個”比較 NC 檔”，將”比較 NC 檔”經過逆向後處理轉回 CL 檔，再與計算“比較 NC 檔”所用的 NC 檔所對應的 CL 檔做平均得到的”比較 CL 檔“來做誤差比較(如圖 3-8。

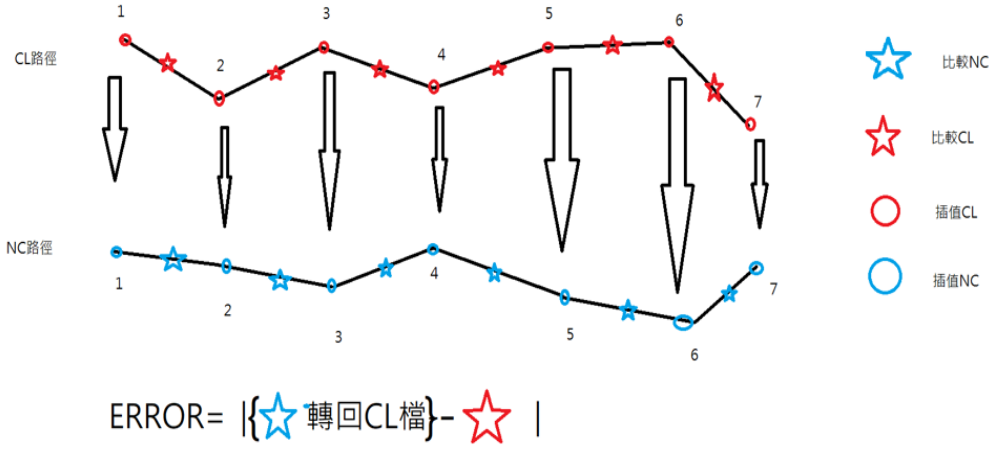


圖 3-8

比較差值數從 1 到 50 與最大加工路徑誤差關係圖(圖 3-9)

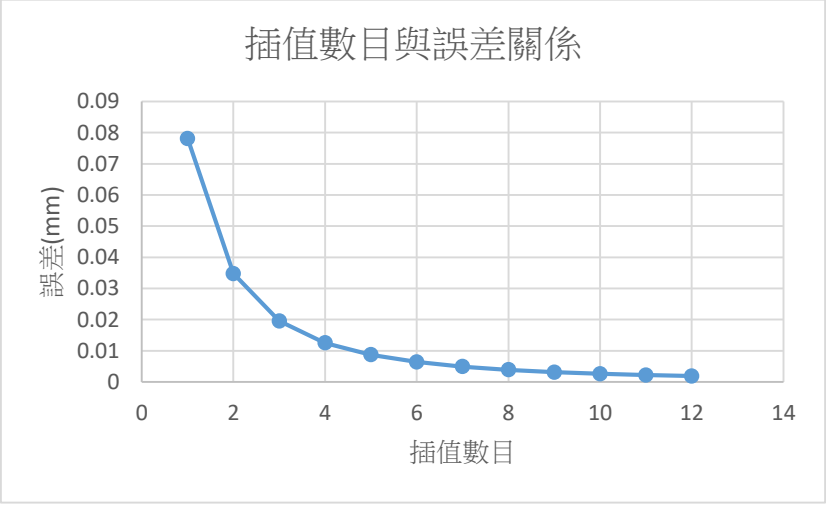
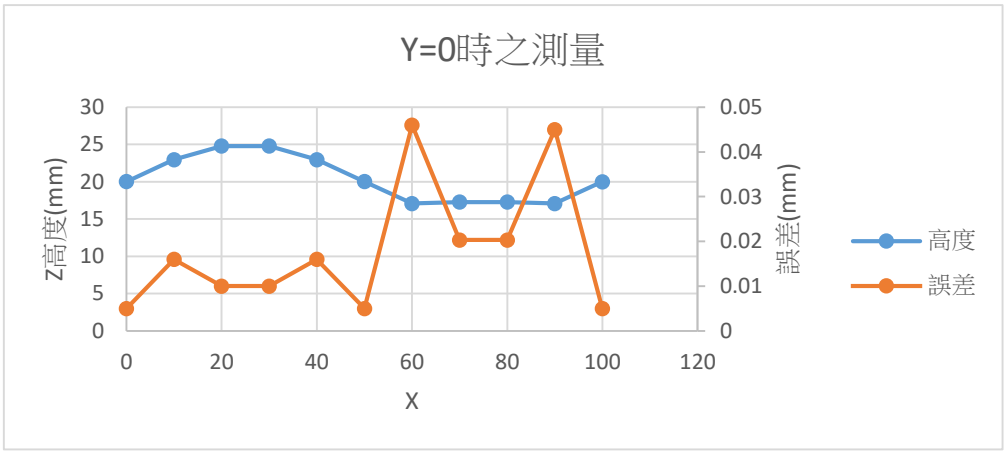


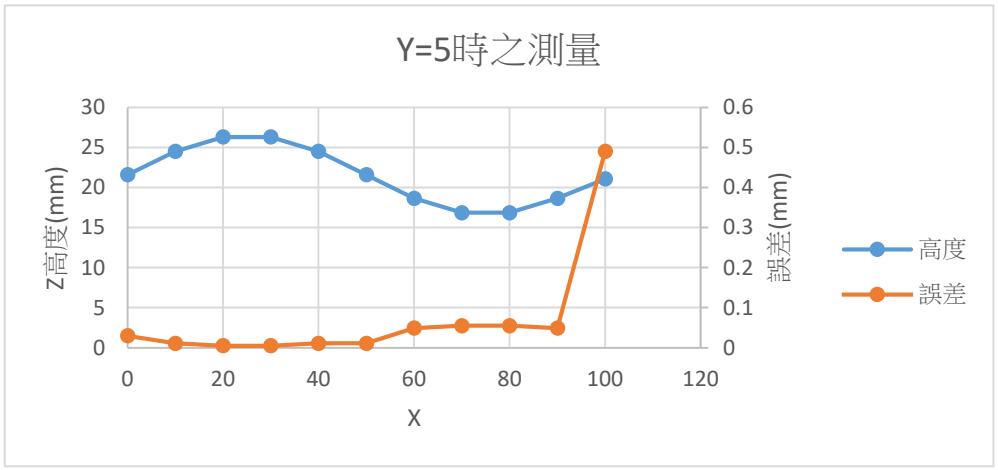
圖 3-9

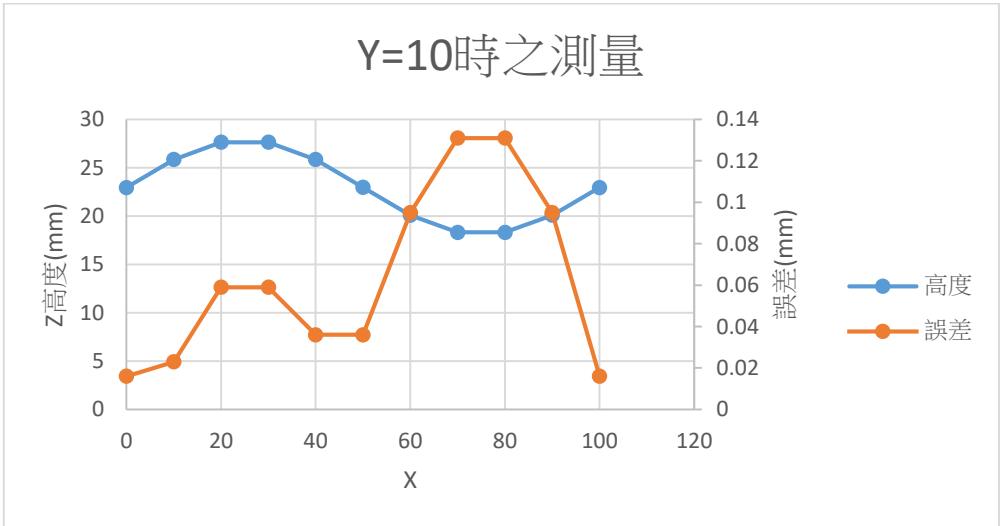
由此可知若要在虛擬環境中做精度 0.01mm 之加工模擬，差值數目至少要 5 個。

3.3 虛擬加工誤差測量

在虛擬環境運用已有的碰撞偵測，可以仿照三次元量床(Coordinate Measuring Machine)測量工件加工後與預期尺寸之誤差。本文製作一把長75mm，尖端0.01mm的虛擬探針，來去測量用3.1章中之加工後的工件。







4. 結論與建議

在 3.1 章比較中，可以得知 NX 之後處理與本文所用之解析解後處理輸出的 NC 碼一致，雖然以數值解後處理所得之 NC 碼與前兩個略微不同，但由於加公所須為刀尖與工件之相對位置與角度，將數值解數值解後處理所得之 NC 碼經過逆向後處理可以得到與後處理前的 CL 檔，也就是說雖然機台各軸移動不同，仍可以得到所要求之刀尖與工件之相對位置與角度。從此可之數值解與解析解皆可以得到 TMV-710A 此構型的加工 NC 碼，但在泛用型後處理上，在解析解求解的過程，不同構型之機台需分開討論，因此缺乏一貫性的後處理流程，另外，數值解求解後處理不須求得解析解即可進行後處理，這使得組裝與後處理整合少了一項繁瑣的步驟，可以大幅增加發展銑床模擬程式的效率。

在 3.2 章比較中，可以清楚地發現當差值數目越多，可以越趨近 CL 檔中 GOTO 之線段，在要求 0.01 精度，插值五項即可達到，但這誤差是與 CL 檔線段之比較，與真實曲線還是有所誤差，因為 CL 檔的 GOTO 也是用線段去趨近真實曲線，因此不僅需要把 CL 檔線段作差值，還要將 GOTO 用更短之線段去趨近才能得到更接近真實曲線的加工路徑，不過，這會造成資料數量變得十分龐大，也會造成工具機控制器上在高速加工時的負擔。為解決此問題，許多學者提出使用參數式曲線，像是 B-SPLINE、NURBS，來做更好之曲線趨近，並減少資料的大小，少數控制器廠商也有讀取參數式曲線之指令，像是新代使用 G06.2 來讀取，但參數式曲線之計算相對於線段趨近起來複雜很多，目前能讀取該指令之控制器也是少數，因此在未來這部份來有很大空間之發展。

在 3.3 章，因為目前虛擬加工環境尚未加入測量加工後工件之功能，因此吾人用類似 CMM 三次元量床之方式來做測量，不同的是使用的探針頭並非圓球狀，也不是用曲面法向量做量測，只用與 Z 軸平行之方向來去做量測，加上虛擬環境在模擬高精度加工時因計算龐大會造成電腦之負擔，所以無法做高精度之量測，因此從 3.3 章可得知量測之誤差仍然過大。為解決此問題可以運用高速計算技術，像是 GPU 高速計算，導入目前之虛擬加工環境來得到更高精度的加工，並加入自動量測加工後工件尺寸之功能，直接用加工後工件檔案讀取之方式來得到加工後工件尺寸，避免再工件精度誤差與測量物精度誤差疊合下讓所測量的尺寸誤差更大。

5. 附錄

5.1 前三行加工路徑之 CL 檔

```
TOOL PATH/VARIABLE_CONTOUR,TOOL,BALL_MILL
TLDATA/MILL,10.0000,5.0000,75.0000,0.0000,0.0000
MSYS/0.0000,0.0000,0.0000,1.0000000,0.0000000,0.0000000,0.0000000,1.0
000000,0.0000000
$$ centerline data
PAINT/PATH
PAINT/SPEED,10
LOAD/TOOL,2
PAINT/COLOR,186
RAPID
GOTO/44.4014,-55.5986,42.8209,-0.2870990,-0.2870990,0.9138645
PAINT/COLOR,211
RAPID
GOTO/47.1290,-52.8710,34.1386
PAINT/COLOR,42
FEDRAT/MMPM,250.0000
GOTO/50.0000,-50.0000,25.0000
PAINT/COLOR,31
GOTO/45.1072,-50.0003,23.4884,-0.2745937,-0.2881959,0.9173557
GOTO/40.1766,-50.0000,22.1062,-0.2374081,-0.2911482,0.9267525
GOTO/37.6874,-50.0000,21.5064,-0.2096495,-0.2930564,0.9328263
GOTO/35.1796,-50.0000,20.9905,-0.1748999,-0.2950974,0.9393229
GOTO/32.6536,-50.0000,20.5721,-0.1366602,-0.2969053,0.9450774
GOTO/30.1123,-50.0000,20.2609,-0.0947925,-0.2983677,0.9497321
GOTO/27.5594,-50.0000,20.0669,-0.0492267,-0.2993540,0.9528714
GOTO/25.0000,-50.0000,20.0000,0.0000023,-0.2997173,0.9540281
GOTO/22.4407,-50.0000,20.0669,0.0492272,-0.2993539,0.9528714
GOTO/19.8878,-50.0000,20.2609,0.0947899,-0.2983678,0.9497324
GOTO/17.3464,-50.0000,20.5721,0.1366558,-0.2969055,0.9450779
GOTO/14.8205,-50.0000,20.9905,0.1748949,-0.2950977,0.9393238
GOTO/12.3126,-50.0000,21.5063,0.2096454,-0.2930567,0.9328272
GOTO/9.8236,-50.0001,22.1068,0.2375525,-0.2911376,0.9267188
GOTO/4.8928,-50.0002,23.4882,0.2746055,-0.2881949,0.9173524
GOTO/0.0000,-50.0000,25.0000,0.2871083,-0.2870982,0.9138618
GOTO/-4.8925,-50.0000,26.5125,0.2746028,-0.2881949,0.9173533
GOTO/-9.8234,-50.0000,27.8936,0.2375583,-0.2911366,0.9267176
GOTO/-12.3125,-50.0000,28.4937,0.2096583,-0.2930552,0.9328248
GOTO/-14.8201,-50.0005,29.0110,0.1748919,-0.2950970,0.9393245
GOTO/-17.3457,-50.0014,29.4322,0.1366461,-0.2969050,0.9450795
GOTO/-19.8872,-50.0014,29.7436,0.0947813,-0.2983670,0.9497335
GOTO/-22.4405,-50.0006,29.9349,0.0492251,-0.2993529,0.9528718
GOTO/-25.0000,-50.0000,29.9999,0.0000096,-0.2997163,0.9540284
GOTO/-27.5594,-50.0006,29.9349,-0.0493409,-0.2993512,0.9528664
GOTO/-30.1127,-50.0015,29.7435,-0.0948647,-0.2983646,0.9497259
GOTO/-32.6542,-50.0015,29.4321,-0.1366219,-0.2969060,0.9450827
GOTO/-35.1798,-50.0005,29.0109,-0.1747600,-0.2951041,0.9393469
GOTO/-37.6875,-50.0000,28.4938,-0.2094767,-0.2930668,0.9328619
GOTO/-40.1766,-50.0000,27.8937,-0.2375673,-0.2911359,0.9267155
GOTO/-45.1075,-50.0000,26.5126,-0.2747177,-0.2881850,0.9173220
GOTO/-50.0000,-50.0000,25.0000,-0.2870990,-0.2870990,0.9138645
PAINT/COLOR,36
GOTO/-50.0000,-45.1075,26.5126,-0.2870971,-0.2748127,0.9176346
PAINT/COLOR,31
GOTO/-45.1075,-45.0872,28.0251,-0.2748763,-0.2739806,0.9216168
GOTO/-40.1766,-45.0686,29.4060,-0.2378342,-0.2750865,0.9315376
GOTO/-37.6875,-45.0606,30.0061,-0.2097638,-0.2761770,0.9379368
GOTO/-35.1795,-45.0536,30.5215,-0.1750380,-0.2774674,0.9446552
GOTO/-32.6535,-45.0480,30.9396,-0.1368643,-0.2786515,0.9505901
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GOTO/-22.4406,-45.0412,31.4453,0.0493238,-0.2803308,0.9586354
GOTO/-19.8877,-45.0438,31.2513,0.0949627,-0.2796429,0.9553962
GOTO/-17.3464,-45.0480,30.9401,0.1368885,-0.2786499,0.9505871
GOTO/-14.8204,-45.0536,30.5218,0.1751701,-0.2774604,0.9446328
GOTO/-12.3125,-45.0606,30.0060,0.2099457,-0.2761661,0.9378993
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GOTO/-4.8925,-45.0872,28.0250,0.2747613,-0.2739902,0.9216483
GOTO/0.0000,-45.1075,26.5126,0.2871064,-0.2748119,0.9176319
GOTO/4.8926,-45.1278,25.0003,0.2744401,-0.2777567,0.9206160
GOTO/9.8235,-45.1464,23.6193,0.2372722,-0.2823552,0.9295039
GOTO/12.3126,-45.1545,23.0193,0.2093419,-0.2849896,0.9353913
GOTO/14.8205,-45.1614,22.5035,0.1745995,-0.2876440,0.9416878
GOTO/17.3464,-45.1670,22.0851,0.1363971,-0.2899528,0.9472715
GOTO/19.8878,-45.1712,21.7740,0.0945957,-0.2917893,0.9517934
GOTO/22.4407,-45.1738,21.5799,0.0491214,-0.2930091,0.9548470
GOTO/25.0000,-45.1747,21.5131,0.0000023,-0.2934528,0.9559736
GOTO/27.5594,-45.1738,21.5799,-0.0491209,-0.2930091,0.9548470
GOTO/30.1123,-45.1712,21.7740,-0.0945982,-0.2917892,0.9517932
GOTO/32.6536,-45.1670,22.0851,-0.1364015,-0.2899526,0.9472709
GOTO/35.1796,-45.1614,22.5035,-0.1746045,-0.2876437,0.9416870
GOTO/37.6874,-45.1545,23.0193,-0.2093461,-0.2849893,0.9353905
GOTO/40.1766,-45.1464,23.6191,-0.2371279,-0.2823656,0.9295375
GOTO/45.1075,-45.1278,25.0002,-0.2744283,-0.2777578,0.9206192
GOTO/50.0000,-45.1075,26.5126,-0.2870971,-0.2748127,0.9176346
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GOTO/50.0000,-40.1766,27.8937,-0.2871092,-0.2379072,0.9278839

PAINT/COLOR,31

GOTO/45.1075,-40.2571,26.3832,-0.2742280,-0.2431946,0.9304060

GOTO/40.1766,-40.3307,25.0039,-0.2367696,-0.2498239,0.9388973

GOTO/37.6874,-40.3626,24.4050,-0.2089520,-0.2532968,0.9445527

GOTO/35.1796,-40.3901,23.8898,-0.1742164,-0.2566616,0.9506700

GOTO/32.6536,-40.4124,23.4721,-0.1360588,-0.2595479,0.9560977

GOTO/30.1123,-40.4289,23.1613,-0.0943392,-0.2618125,0.9604969

GOTO/27.5594,-40.4393,22.9675,-0.0489792,-0.2632963,0.9634709

GOTO/25.0000,-40.4428,22.9008,0.0000023,-0.2638293,0.9645694

GOTO/22.4407,-40.4393,22.9675,0.0489797,-0.2632962,0.9634709

GOTO/19.8878,-40.4289,23.1613,0.0943366,-0.2618125,0.9604972

GOTO/17.3464,-40.4124,23.4720,0.1360544,-0.2595481,0.9560983

GOTO/14.8205,-40.3901,23.8898,0.1742114,-0.2566619,0.9506709

GOTO/12.3126,-40.3626,24.4049,0.2089478,-0.2532971,0.9445535

GOTO/9.8235,-40.3307,25.0041,0.2369137,-0.2498143,0.9388635

GOTO/4.8926,-40.2571,26.3833,0.2742398,-0.2431934,0.9304029

GOTO/0.0000,-40.1766,27.8936,0.2871185,-0.2379066,0.9278812

GOTO/-4.8925,-40.0960,29.4040,0.2749718,-0.2345603,0.9324012

GOTO/-9.8234,-40.0225,30.7832,0.2381618,-0.2331454,0.9428267

GOTO/-12.3125,-39.9905,31.3824,0.2103030,-0.2330525,0.9494520

GOTO/-14.8204,-39.9630,31.8975,0.1755123,-0.2332849,0.9564380

GOTO/-17.3464,-39.9408,32.3153,0.1371843,-0.2335914,0.9626087

GOTO/-19.8877,-39.9242,32.6260,0.0951828,-0.2339100,0.9675879

GOTO/-22.4406,-39.9138,32.8197,0.0494430,-0.2341662,0.9709385

GOTO/-25.0000,-39.9103,32.8865,0.0000096,-0.2342728,0.9721709

GOTO/-27.5593,-39.9139,32.8195,-0.0495593,-0.2341653,0.9709328

GOTO/-30.1122,-39.9242,32.6255,-0.0952666,-0.2339094,0.9675798

GOTO/-32.6535,-39.9408,32.3147,-0.1371600,-0.2335937,0.9626116

GOTO/-35.1795,-39.9631,31.8971,-0.1753799,-0.2332914,0.9564607

GOTO/-37.6875,-39.9905,31.3825,-0.2101208,-0.2330616,0.9494901

GOTO/-40.1766,-40.0225,30.7832,-0.2381709,-0.2331447,0.9428246

GOTO/-45.1075,-40.0960,29.4042,-0.2750869,-0.2345518,0.9323694

GOTO/-50.0000,-40.1766,27.8937,-0.2871092,-0.2379072,0.9278839

PAINT/COLOR,36

GOTO/-50.0119,-37.6867,28.4903,-0.2872523,-0.2066629,0.9352949

GOTO/-50.0000,-35.1795,29.0092,-0.2870992,-0.1752055,0.9417415

5.2 前三行加工路徑之解析解後處理 NC 碼

X70.711 Y18.271 Z21.124 A23.955 C315

X70.710678 Y18.27087 Z40.624495 A23.955018 C315.

X70.710678 Y18.270838 Z31.123867 A23.955018 C315.

X70.710678 Y18.270869 Z21.123902 A23.955018 C315.

X67.147925 Y12.647645 Z21.91806 A23.457486 C316.384526

X62.734816 Y3.436297 Z24.041184 A22.065882 C320.805505

X59.743114 Y-2.523146 Z25.46994 A21.120241 C324.420464

X55.756553 Y-9.493415 Z27.105278 A20.061845 C329.3454

X50.568162 Y-16.761068 Z28.726589 A19.077489 C335.28423

X43.838238 Y-23.99386 Z30.301036 A18.243966 C342.374759

X35.307357 Y-30.595754 Z31.789646 A17.660397 C350.66168

X24.999616 Y-35.712901 Z33.14704 A17.440617 C0.00044

X14.030023 Y-38.326619 Z34.250993 A17.660397 C9.338416

X3.815155 Y-38.372371 Z35.040625 A18.243911 C17.624782

X-5.147847 Y-36.518866 Z35.559563 A19.077401 C24.715055

X-12.742983 Y-33.439991 Z35.850261 A20.061694 C30.653856

X-19.077217 Y-29.66093 Z35.95232 A21.120098 C35.578978

X-23.998654 Y-25.83492 Z35.911691 A22.071021 C39.212581

X-30.949494 Y-18.991539 Z35.647402 A23.457961 C43.616803

X-35.355961 Y-14.038183 Z35.478694 A23.955399 C45.001008

X-38.033454 Y-11.595479 Z35.734643 A23.457831 C43.616521

X-39.221642 Y-12.149139 Z36.607043 A22.071204 C39.213362

X-39.106219 Y-13.776598 Z37.307465 A21.120479 C35.580785

X-38.241724 Y-16.494148 Z38.200319 A20.061577 C30.653485

X-36.661675 Y-19.917065 Z39.192802 A19.077121 C24.713547

X-34.092164 Y-23.968212 Z40.276991 A18.24371 C17.623326

X-30.256182 Y-28.394299 Z41.444752 A17.660322 C9.338056

X-25.001602 Y-32.714875 Z42.686896 A17.440559 C0.001835

X-19.060811 Y-36.13062 Z43.90883 A17.661342 C350.640313

X-13.546539 Y-38.346992 Z45.017997 A18.245101 C342.361994

X-8.762709 Y-39.673252 Z46.024444 A19.07656 C335.290381

X-4.792321 Y-40.442453 Z46.941604 A20.057836 C329.366076

X-1.585413 Y-40.921131 Z47.786015 A21.114579 C324.443779

X0.483055 Y-41.442717 Z48.48528 A22.071524 C320.785507

X1.850024 Y-43.23041 Z49.468105 A23.462336 C316.370525

X0. Y-46.34911 Z49.833803 A23.955018 C315.

X-1.988809 Y-43.281357 Z49.432538 A23.41731 C313.747607

X0.089726 Y-40.139565 Z49.01275 A22.836397 C314.906497

X-0.916239 Y-38.270382 Z47.976681 A21.324219 C319.153973

X-2.757557 Y-37.694576 Z47.252734 A20.292094 C322.78236

X-5.715556 Y-37.15286 Z46.38406 A19.151362 C327.754563

X-9.449169 Y-36.30635 Z45.444468 A18.08628 C333.841273

X-14.015008 Y-34.866091 Z44.422576 A17.178666 C341.22779

X-19.317562 Y-32.466015 Z43.305708 A16.538273 C349.997985

X-25.001541 Y-28.776345 Z42.080351 A16.295405 C0.00196

X-29.906147 Y-24.15383 Z40.836864 A16.537146 C9.97897

X-33.315387 Y-19.503631 Z39.672889 A17.177153 C18.756747

X-35.431918 Y-15.349408 Z38.601097 A18.086833 C26.162866

X-36.583498 Y-11.935814 Z37.62905 A19.155274 C32.265598

X-37.072041 Y-9.30801 Z36.759846 A20.298288 C37.242653

X-36.906703 Y-7.808786 Z36.085193 A21.323888 C40.844882

X-35.380888 Y-7.514278 Z35.271341 A22.831746 C45.080511

X-32.585885 Y-10.135822 Z35.077524 A23.417699 C46.253404

X-28.237636 Y-15.147465 Z35.305272 A22.983696 C44.655875

X-21.52387 Y-21.913596 Z35.622471 A21.642386 C40.041421

X-16.808611 Y-25.646262 Z35.685986 A20.708546 C36.299507

X-10.76452 Y-29.294515 Z35.603087 A19.66304 C31.257691

X-3.529641 Y-32.224701 Z35.328306 A18.689056 C25.192828

X4.98809 Y-33.921931 Z34.821989 A17.862867 C17.962269

X14.662934 Y-33.729867 Z34.041093 A17.283384 C9.516832

X24.999646 Y-31.003877 Z32.942122 A17.064777 C0.000449

X34.648952 Y-25.836313 Z31.585035 A17.283384 C350.483263

X42.57526 Y-19.245343 Z30.092105 A17.862904 C342.037281

X48.774 Y-12.062959 Z28.508278 A18.689163 C334.806445

X53.506985 Y-4.862165 Z26.872868 A19.663176 C328.741554

X57.105421 Y2.042253 Z25.218682 A20.708675 C323.699916

X59.800152 Y7.964149 Z23.766387 A21.637166 C319.976785

X63.804746 Y17.203455 Z21.583872 A22.983227 C315.34547

X67.159479 Y23.007911 Z20.72283 A23.41731 C313.747607

X62.838186 Y29.795796 Z19.642637 A21.89268 C309.646153

X60.048275 Y23.548522 Z20.575777 A21.501808 C311.567689

X56.90386 Y13.954549 Z22.817016 A20.132811 C316.536759

X54.756824 Y7.824142 Z24.291722 A19.169256 C320.479773

X51.791303 Y0.627607 Z25.962441 A18.071528 C325.832179

X47.683784 Y-6.986721 Z27.609722 A17.04053 C332.335815

X42.034498 Y-14.716456 Z29.200318 A16.158214 C340.184329

X34.490358 Y-21.941599 Z30.695611 A15.534171 C349.462112

X24.999647 Y-27.691612 Z32.05085 A15.297398 C0.000499

X14.666366 Y-30.751896 Z33.144583 A15.534171 C10.537998

X5.005394 Y-30.996699 Z33.917243 A16.158152 C19.815168

X-3.398986 Y-29.182164 Z34.412523 A17.040412 C27.663405

X-10.420835 Y-26.068449 Z34.673249 A18.071362 C34.167026

X-16.186418 Y-22.229518 Z34.739229 A19.169116 C39.519629

X-20.624631 Y-18.326687 Z34.655216 A20.138436 C43.481746

X-26.873712 Y-11.25566 Z34.287161 A21.502293 C48.433675

X-30.936403 Y-5.926866 Z33.997846 A21.893095 C50.354829

X-33.680171 Y-2.936329 Z34.123978 A21.187734 C49.534693

X-35.471648 Y-2.853094 Z34.87126 A19.468185 C45.60981

X-35.932289 Y-4.227456 Z35.515655 A18.29516 C42.06261

X-35.868776 Y-6.870554 Z36.358341 A16.973869 C36.956037

X-35.184098 Y-10.52496 Z37.309337 A15.717574 C30.425

X-33.468815 Y-15.238393 Z38.365984 A14.62754 C22.142421

X-30.202294 Y-20.775265 Z39.521613 A13.846948 C11.922592

X-25.001635 Y-26.408768 Z40.764374 A13.54876 C0.002348

X-18.697657 Y-30.81187 Z41.996454 A13.848313 C348.050124

X-12.828687 Y-33.474971 Z43.126703 A14.629377 C337.839919

X-7.934617 Y-34.898874 Z44.167413 A15.716961 C329.579679

X-4.105891 Y-35.624906 Z45.130356 A16.969413 C323.0655

X-1.21312 Y-36.038828 Z46.026361 A18.288204 C317.963202

X0.495766 Y-36.539506 Z46.779576 A19.468546 C314.38901

X1.244344 Y-38.398525 Z47.876032 A21.192774 C310.452443

X-0.966259 Y-41.651221 Z48.35355 A21.89268 C309.646153

X1.384655 Y-41.396212 Z47.507207 A20.72416 C305.733027

X3.983294 Y-40.968237 Z46.672602 A19.653894 C301.394097

5.3 前三行加工路徑之數值解後處理 NC 碼

x: 70.71068 y: 18.14587 z: -134.33797 a: 23.83692 c: -45
x: 70.71068 y: 18.16542 z: -143.83858 a: 23.83692 c: -45
x: 70.71068 y: 18.18607 z: -153.83853 a: 23.83692 c: -45
x: 67.1699 y: 12.9861 z: -153.22086 a: 23.54542 c: -43.87059
x: 62.82324 y: 3.91087 z: -151.12475 a: 22.17472 c: -39.57977
x: 59.77278 y: -2.41825 z: -149.56336 a: 21.14094 c: -35.67048
x: 55.75765 y: -9.49188 z: -147.89571 a: 20.06093 c: -30.65711
x: 50.78467 y: -16.38684 z: -146.37139 a: 19.13171 c: -25.10842
x: 43.95743 y: -23.8521 z: -144.73558 a: 18.2583 c: -17.80277
x: 35.72403 y: -30.25787 z: -143.29766 a: 17.68525 c: -9.8724
x: 25.19289 y: -35.62152 z: -141.8829 a: 17.43926 c: -0.22125
x: 14.56047 y: -38.21647 z: -140.81111 a: 17.63246 c: 8.76397
x: 3.98998 y: -38.37839 z: -139.97597 a: 18.22508 c: 17.43814
x: -5.151 y: -36.51999 z: -139.44147 a: 19.07594 c: 24.71848
x: -12.43304 y: -33.57934 z: -139.16349 a: 19.99304 c: 30.30296
x: -18.98759 y: -29.72115 z: -139.04915 a: 21.09249 c: 35.47166
x: -23.72199 y: -26.06979 z: -139.07926 a: 21.96963 c: 38.86051
x: -30.93952 y: -19.00504 z: -139.35166 a: 23.45143 c: 43.60236
x: -35.18921 y: -14.28753 z: -139.47896 a: 23.85463 c: 44.73141
x: -38.03451 y: -11.5949 z: -139.26596 a: 23.45727 c: 43.61837
x: -39.28527 y: -12.04783 z: -138.41543 a: 22.10166 c: 39.32557
x: -39.24546 y: -13.56786 z: -137.73794 a: 21.17699 c: 35.81951
x: -38.24328 y: -16.49351 z: -136.80052 a: 20.06066 c: 30.656
x: -36.92253 y: -19.62267 z: -135.87105 a: 19.13136 c: 25.10641
x: -34.22145 y: -23.8522 z: -134.75026 a: 18.25811 c: 17.80148
x: -30.68122 y: -28.09678 z: -133.62929 a: 17.68519 c: 9.87264
x: -25.19498 y: -32.62366 z: -132.343 a: 17.43921 c: 0.22365
x: -19.60089 y: -35.97671 z: -131.16775 a: 17.63327 c: -8.78366
x: -13.73185 y: -38.32613 z: -130.00858 a: 18.22621 c: -17.45092
x: -8.75919 y: -39.67541 z: -128.97639 a: 19.07511 c: -24.71303
x: -5.16501 y: -40.49384 z: -128.1172 a: 19.98934 c: -30.28348
x: -1.70273 y: -40.9509 z: -127.23481 a: 21.08699 c: -35.44883
x: 0.08637 y: -41.56629 z: -126.588 a: 21.96945 c: -38.86014
x: 1.83301 y: -43.23877 z: -125.53665 a: 23.45579 c: -43.615
x: -0.32949 y: -46.46996 z: -125.24733 a: 23.85523 c: -44.73302
x: -2.05635 y: -43.25238 z: -125.55137 a: 23.43968 c: -46.1949
x: 0.37968 y: -39.98677 z: -125.89959 a: 22.96235 c: -45.35399
x: -0.89406 y: -38.2646 z: -127.01977 a: 21.32935 c: -40.86708
x: -2.35888 y: -37.59317 z: -127.67538 a: 20.39232 c: -37.60686
x: -5.58888 y: -37.13683 z: -128.59619 a: 19.17546 c: -32.37304
x: -9.44591 y: -36.30831 z: -129.55615 a: 18.08504 c: -26.16213
x: -13.56853 y: -34.92621 z: -130.51444 a: 17.22502 c: -19.26043
x: -19.13313 y: -32.52472 z: -131.66842 a: 16.54769 c: -10.21689
x: -24.50313 y: -29.03883 z: -132.8432 a: 16.29506 c: -0.63015
x: -29.74416 y: -24.28146 z: -134.13454 a: 16.52457 c: 9.74998
x: -32.98059 y: -19.84909 z: -135.25508 a: 17.12515 c: 18.22989
x: -35.34006 y: -15.47063 z: -136.37531 a: 18.06034 c: 26.00256
x: -36.58535 y: -11.93479 z: -137.37191 a: 19.15419 c: 32.26911
x: -36.92675 y: -9.56078 z: -138.18748 a: 20.2217 c: 36.95071
x: -36.90827 y: -7.80768 z: -138.91569 a: 21.32302 c: 40.84814
x: -35.33571 y: -7.6022 z: -139.71178 a: 22.79436 c: 44.98936
x: -32.43718 y: -10.41333 z: -139.88648 a: 23.27674 c: 45.98091
x: -28.36047 y: -15.00791 z: -139.71954 a: 23.03489 c: 44.85418
x: -21.81 y: -21.67117 z: -139.39401 a: 21.74671 c: 40.44317
x: -16.88035 y: -25.60061 z: -139.31471 a: 20.72888 c: 36.39364
x: -10.76661 y: -29.29497 z: -139.39756 a: 19.6621 c: 31.26028
x: -3.86726 y: -32.14864 z: -139.65002 a: 18.74242 c: 25.59381
x: 4.83259 y: -33.92325 z: -140.1649 a: 17.87695 c: 18.14369
x: 14.2036 y: -33.83783 z: -140.90375 a: 17.30776 c: 10.06136
x: 24.82164 y: -31.099 z: -142.02992 a: 17.06328 c: 0.22598
x: 34.23839 y: -26.19782 z: -143.32324 a: 17.25525 c: -8.93117
x: 42.46327 y: -19.3961 z: -144.871 a: 17.84406 c: -17.77261
x: 48.77567 y: -12.06134 z: -146.493 a: 18.68769 c: -25.19711
x: 53.37867 y: -5.23283 z: -148.02087 a: 19.59495 c: -30.90014
x: 57.07838 y: 1.91851 z: -149.74178 a: 20.68135 c: -36.19048
x: 59.76584 y: 7.70188 z: -151.1399 a: 21.57598 c: -39.80109
x: 63.801 y: 16.75149 z: -153.2263 a: 22.86706 c: -44.29625
x: 67.16513 y: 22.92271 z: -154.23846 a: 23.3977 c: -46.18615
x: 62.88059 y: 29.6455 z: -155.31194 a: 21.95546 c: -50.16347
x: 60.00884 y: 23.89717 z: -154.56998 a: 21.56245 c: -48.74606
x: 56.90455 y: 13.9806 z: -152.1924 a: 20.13714 c: -43.4877
x: 54.7888 y: 8.10353 z: -150.79815 a: 19.22631 c: -39.78089
x: 51.79206 y: 0.62955 z: -149.03844 a: 18.07055 c: -34.171
x: 47.8387 y: -6.59402 z: -147.48978 a: 17.09697 c: -28.09819
x: 42.03631 y: -14.71537 z: -145.80091 a: 16.15642 c: -19.81941
x: 34.85303 y: -21.56787 z: -144.39213 a: 15.56012 c: -11.13959
x: 25.17625 y: -27.58744 z: -142.97896 a: 15.29559 c: -0.25004
x: 15.15955 y: -30.6186 z: -141.91688 a: 15.50334 c: 9.89253
x: 5.16706 y: -30.99821 z: -141.09888 a: 16.13779 c: 19.60826
x: -3.40244 y: -29.18338 z: -140.58835 a: 17.03886 c: 27.66792
x: -10.14354 y: -26.20218 z: -140.33853 a: 17.99922 c: 33.78672
x: -16.10803 y: -22.28762 z: -140.26128 a: 19.1404 c: 39.40443
x: -20.47685 y: -18.46672 z: -140.33635 a: 20.07454 c: 43.24697
x: -26.87477 y: -11.2553 z: -140.71329 a: 21.50175 c: 48.43568
x: -30.91698 y: -5.958 z: -140.99446 a: 21.88311 c: 50.31144
x: -33.69492 y: -2.88709 z: -140.88255 a: 21.21786 c: 49.57261

x: -35.53955 y: -2.67589 z: -140.16376 a: 19.53981 c: 45.79578

x: -35.93395 y: -4.22567 z: -139.48529 a: 18.29426 c: 42.06706

x: -36.00771 y: -6.58585 z: -138.69629 a: 17.05152 c: 37.30343

x: -35.2611 y: -10.39745 z: -137.71472 a: 15.74312 c: 30.59732

x: -33.47174 y: -15.23709 z: -136.63535 a: 14.62566 c: 22.1481

x: -30.60428 y: -20.39306 z: -135.55159 a: 13.88127 c: 12.59529

x: -25.19977 y: -26.28898 z: -134.26554 a: 13.5473 c: 0.28724

x: -19.26326 y: -30.6185 z: -133.08095 a: 13.81117 c: -11.22385

x: -13.01685 y: -33.4533 z: -131.90033 a: 14.60483 c: -21.93691

x: -7.92918 y: -34.9014 z: -130.83329 a: 15.71543 c: -30.42643

x: -4.4517 y: -35.69541 z: -129.931 a: 16.88388 c: -36.56115

x: -1.31591 y: -36.07522 z: -128.99549 a: 18.25467 c: -41.92959

x: 0.16007 y: -36.68585 z: -128.29906 a: 19.34448 c: -45.27182

x: 1.23187 y: -38.40781 z: -127.12899 a: 21.18514 c: -49.53572

x: -1.01973 y: -41.70316 z: -126.6789 a: 21.84849 c: -50.30608

5.4 前三行加工路徑之 NX 後處理 NC 碼

X70.711 Y18.271 Z21.124 A23.955 C315.

X67.148 Y12.648 Z21.918 A23.457 C316.385

X62.735 Y3.436 Z24.041 A22.066 C320.806

X59.743 Y-2.523 Z25.47 A21.12 C324.42

X55.757 Y-9.493 Z27.105 A20.062 C329.345

X50.568 Y-16.761 Z28.727 A19.077 C335.284

X43.838 Y-23.994 Z30.301 A18.244 C342.375

X35.307 Y-30.596 Z31.79 A17.66 C350.662

X25. Y-35.713 Z33.147 A17.441 C0.0

X14.03 Y-38.327 Z34.251 A17.66 C9.338

X3.815 Y-38.372 Z35.041 A18.244 C17.625

X-5.148 Y-36.519 Z35.56 A19.077 C24.715

X-12.743 Y-33.44 Z35.85 A20.062 C30.654

X-19.077 Y-29.661 Z35.952 A21.12 C35.579

X-23.999 Y-25.835 Z35.912 A22.071 C39.213

X-30.95 Y-18.992 Z35.647 A23.458 C43.617

X-35.356 Y-14.038 Z35.479 A23.955 C45.001

X-38.033 Y-11.595 Z35.735 A23.458 C43.617

X-39.222 Y-12.149 Z36.607 A22.071 C39.213

X-39.106 Y-13.777 Z37.307 A21.12 C35.581

X-38.242 Y-16.494 Z38.2 A20.062 C30.653

X-36.662 Y-19.917 Z39.193 A19.077 C24.714

X-34.092 Y-23.968 Z40.277 A18.244 C17.623

X-30.256 Y-28.394 Z41.445 A17.66 C9.338

X-25.002 Y-32.715 Z42.687 A17.441 C.002

X-19.061 Y-36.131 Z43.909 A17.661 C350.64

X-13.547 Y-38.347 Z45.018 A18.245 C342.362

X-8.763 Y-39.673 Z46.024 A19.077 C335.29

X-4.792 Y-40.442 Z46.942 A20.058 C329.366

X-1.585 Y-40.921 Z47.786 A21.115 C324.444

X.483 Y-41.443 Z48.485 A22.072 C320.786

X1.85 Y-43.23 Z49.468 A23.462 C316.371

X0.0 Y-46.349 Z49.834 A23.955 C315.

X-1.989 Y-43.281 Z49.433 A23.417 C313.748

X.09 Y-40.14 Z49.013 A22.836 C314.906

X-.916 Y-38.27 Z47.977 A21.324 C319.154

X-2.758 Y-37.695 Z47.253 A20.292 C322.782

X-5.716 Y-37.153 Z46.384 A19.151 C327.755

X-9.449 Y-36.306 Z45.444 A18.086 C333.841

X-14.015 Y-34.866 Z44.423 A17.179 C341.228

X-19.318 Y-32.466 Z43.306 A16.538 C349.998

X-25.002 Y-28.776 Z42.08 A16.295 C.002

X-29.906 Y-24.154 Z40.837 A16.537 C9.979

X-33.315 Y-19.504 Z39.673 A17.177 C18.757

X-35.432 Y-15.349 Z38.601 A18.087 C26.163

X-36.584 Y-11.936 Z37.629 A19.155 C32.266

X-37.072 Y-9.308 Z36.76 A20.298 C37.243

X-36.907 Y-7.809 Z36.085 A21.324 C40.845

X-35.381 Y-7.514 Z35.271 A22.832 C45.081

X-32.586 Y-10.136 Z35.078 A23.418 C46.253

X-28.238 Y-15.147 Z35.305 A22.984 C44.656

X-21.524 Y-21.914 Z35.622 A21.642 C40.041

X-16.809 Y-25.646 Z35.686 A20.709 C36.3

X-10.765 Y-29.295 Z35.603 A19.663 C31.258

X-3.53 Y-32.225 Z35.328 A18.689 C25.193

X4.988 Y-33.922 Z34.822 A17.863 C17.962

X14.663 Y-33.73 Z34.041 A17.283 C9.517

X25. Y-31.004 Z32.942 A17.065 C0.0

X34.649 Y-25.836 Z31.585 A17.283 C350.483

X42.575 Y-19.245 Z30.092 A17.863 C342.037

X48.774 Y-12.063 Z28.508 A18.689 C334.806

X53.507 Y-4.862 Z26.873 A19.663 C328.742

X57.105 Y2.042 Z25.219 A20.709 C323.7

X59.8 Y7.964 Z23.766 A21.637 C319.977

X63.805 Y17.203 Z21.584 A22.983 C315.345

X67.159 Y23.008 Z20.723 A23.417 C313.748

X62.838 Y29.796 Z19.643 A21.893 C309.646

X60.048 Y23.548 Z20.576 A21.502 C311.568

X56.904 Y13.955 Z22.817 A20.133 C316.537

X54.757 Y7.824 Z24.292 A19.169 C320.48

X51.791 Y.628 Z25.962 A18.072 C325.832

X47.684 Y-6.987 Z27.61 A17.041 C332.336

X42.035 Y-14.717 Z29.2 A16.158 C340.184

X34.49 Y-21.942 Z30.696 A15.534 C349.462

X25. Y-27.692 Z32.051 A15.297 C.001

X14.666 Y-30.752 Z33.145 A15.534 C10.538

X5.005 Y-30.997 Z33.917 A16.158 C19.815

X-3.399 Y-29.182 Z34.413 A17.04 C27.663

X-10.421 Y-26.068 Z34.673 A18.071 C34.167

X-16.186 Y-22.23 Z34.739 A19.169 C39.52

X-20.625 Y-18.327 Z34.655 A20.138 C43.482

X-26.874 Y-11.256 Z34.287 A21.502 C48.434

X-30.936 Y-5.927 Z33.998 A21.893 C50.355

X-33.68 Y-2.936 Z34.124 A21.188 C49.535

X-35.472 Y-2.853 Z34.871 A19.468 C45.61

X-35.932 Y-4.227 Z35.516 A18.295 C42.063

X-35.869 Y-6.871 Z36.358 A16.974 C36.956

X-35.184 Y-10.525 Z37.309 A15.718 C30.425

X-33.469 Y-15.238 Z38.366 A14.628 C22.142

X-30.202 Y-20.775 Z39.522 A13.847 C11.923

X-25.002 Y-26.409 Z40.764 A13.549 C.002

X-18.698 Y-30.812 Z41.996 A13.848 C348.05

X-12.829 Y-33.475 Z43.127 A14.629 C337.84

X-7.935 Y-34.899 Z44.167 A15.717 C329.58

X-4.106 Y-35.625 Z45.13 A16.969 C323.065

X-1.213 Y-36.039 Z46.026 A18.288 C317.963

X.496 Y-36.539 Z46.78 A19.469 C314.389

X1.244 Y-38.399 Z47.876 A21.193 C310.452

X-.966 Y-41.651 Z48.354 A21.893 C309.646

X1.385 Y-41.396 Z47.507 A20.724 C305.733

X3.983 Y-40.968 Z46.673 A19.654 C301.394

6. 參考資料

[1] R.-S. Lee and C.-H. She, "Developing a postprocessor for three types of five-axis machine tools," *The International Journal of Advanced Manufacturing Technology,* vol. 13, no. 9, pp. 658-665, 1997.

[2] K. Mei, "Studies on Virtual Multi-Axis Milling Machine Construction and Postprocessor Program Integration," Master Thesis, National Cheng-Kung University, Taiwan, 2009.

[3] I. ISO, "841: 2001, Industrial automation systems and integration--Numerical control of machines--Coordinate system and motion nomenclature," *Geneva, Switzerland, ISO,* 2001.

[4] 數值控制機械 ,李榮顯 ,1991