

# Spiral Toolpath Definition and G-code Generation for Single Point Incremental Forming

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## ABSTRACT

*The research to date has not been able to confirm earlier findings showing the commercial availability of the tool path definition package for Single Point Incremental Forming (SPIF). There has been substantial research undertaken on the tool-path definition for SPIF by using CAM package or Matlab script. However, the coordinate points from Matlab must get changed to G-code to introduce in the CNC mill. Previous studies on SPIF have not dealt with the conversion of Matlab script into G-code. In the current study, a methodology has been proposed to convert the tool path trajectories generated using Matlab script into G-code. Three different shapes i.e. the truncated cone, pyramid, and hyperbola were chosen for the definition of tool-path trajectory. The method was tested using Simco edit software and successfully working. This study fills a gap in the literature by introducing a method to convert Matlab script into G-code.*

**Keywords:** SPIF; Toolpath Definition; Numerical Simulation; Spiral Toolpath; G-code Generation

## Introduction

Single point incremental forming (SPIF), is a relatively new process for manufacturing sheet metal parts. It is well suited for small batch production or prototyping. It can be executed by using a CNC mill. It has a high potential economic payoff [1]-[3]. Based on recent reviews, SPIF is on the progress of industrialization. A CAM package with the feature for the tool-path definition of SPIF has not been introduced [4].

Two of the most common methods for the definition of tool path are the contour and the spiral. The contour tool path uses CAM packages whereas; the spiral tool path uses CAM or programming script. The profile tool path created by using a CAM package can produce complex geometry but it produces scarring on the surface of the part. The helical tool path is more suitable for Incremental Sheet Forming (ISF). It completely eliminates scarring on the surface of the formed part and produces homogeneous thinning [5].

Studies have shown that tool-path created in Matlab script has widely used for the numerical simulation of SPIF [5,6]. In contrast, the CAM developed toolpath has been using for an experimental investigation [7]-[9]. CNC mill does not accept the coordinate points created from Matlab. That is because G-code is the programming language for CNC that instructs machines where and how to move. Because of this, the coordinate points from Matlab must get changed to G-code to introduce in the CNC Mill.

Prior studies have not been able to establish a method to convert coordinate points into G-code. In this study, a method to convert the coordinate points into G-code has introduced. The results of this experiment were found to be satisfactory.

## Methodology

Figure 1 shows the procedures followed to get a 3D line plot of the required sample part and conversion of the coordinate points into G-code.

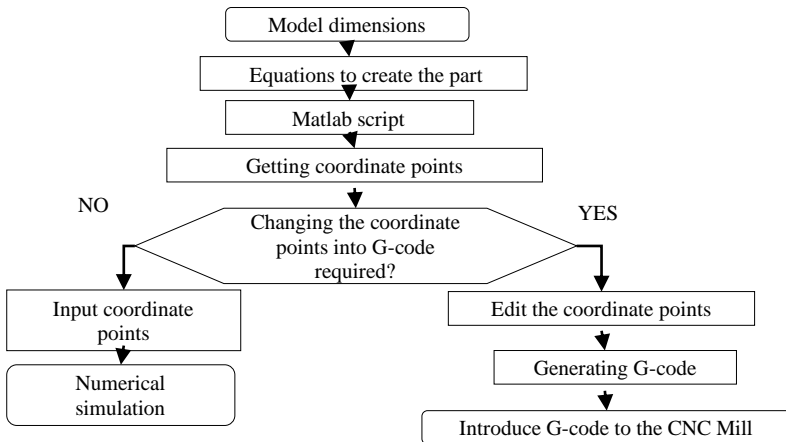


Figure 1: Method used for the tool-path definition and G-code generation

### Sample Parts

The first sample part used in this study is the truncated cone. The basic parameters required to formulate the truncated cone are depicted in Figure 2.

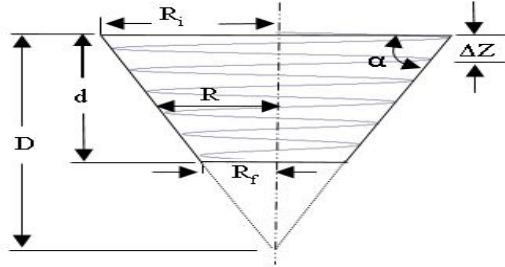


Figure 2: Parameters to formulate the truncated cone

Equations (1)–(5) are used for the formulation of the truncated cone.

$$\Delta r = \frac{\Delta Z}{\tan(\alpha)} \quad (1)$$

$$N = \frac{d}{\Delta Z} \quad (2)$$

$$X = R \cos(\theta) \quad (3)$$

$$Y = R \sin(\theta) \quad (4)$$

$$Z = -\left(\left(\frac{\Delta Z}{360}\right)\theta\right) \quad (5)$$

This section has attempted to provide the Matlab script that used to define the spiral tool-path for the truncated cone. The “plot 3” function was used to create a three-dimensional plot. Figure 3 depicts the isometric view of the Truncated cone.

```
clear
clc
dh=0.5;    %step depth
a=45;     %angle of inclination of the cone
h=30;     %Depth of the cone
R1=50;    %largest radius of the cone (top part)
D=R1*tand(a);
N=h/dh;   %Number of loops or contour
m=1;
for n=0:1:360*N %dividing a loop into 360 angles
```

```

Z (m)=0-((dh/360)* n);
R=R1-(((dh/360)* n)/tand(a)); %radius at anydepth
X (m)=R*cosd(n);
Y (m)=R*sind(n);
m=m+1;
end
plot3(Y, X, Z, 'b') % 3D visualization of helix

```

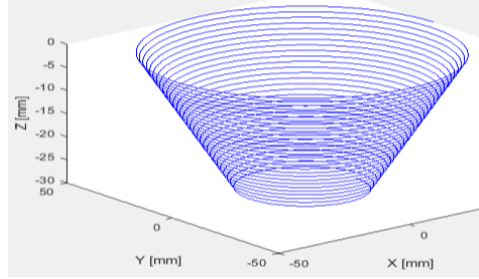


Figure 3: Isometric view of the truncated cone

The second sample part is Hyperbola. The parameters used to formulate this part are presented in Figure 4.

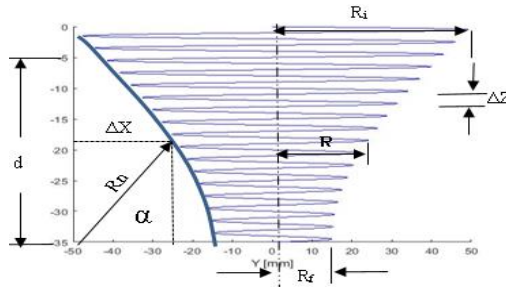


Figure 4: Parameters to formulate the Hyperbola

The number of loops and the coordinate points of X, Y and Z are defined by using equations (2) – (5). Equations (6) – (9) are used to formulate the rest of the parameters.

$$\Delta x = R_n \cos \alpha \quad (6)$$

$$R = R_i - \Delta X \quad (7)$$

$$\Delta R = \frac{\pi}{2(360 \cdot N)} \quad (8)$$

$$\beta = \frac{\pi}{2} - (\Delta R \cdot \theta) \quad (9)$$

This section has attempted to provide the Matlab script used to define the spiral tool-path for the hyperbolic part. Figure 5 depicts the isometric view of the hyperbola.

```

clc
clear
% NOTE: input parameters: dh, h, R1, r1
dh=1;      %Step Depth
h=30;      %depth of the hyperbola
R1=50;     %Initial radius of the circle
r1=h;
N=h/dh;    %Number of loops
m=1;
Ra=pi/(2*360*N); %change in radius on the arc
within one loop

for n=0:1:360*N
    theta=(pi/2)-(Ra*n); %change in angle on the arc
    z(m)=0-((dh/360)*n);
    R=R1-r1*cos(theta); % Radius at any intermediate
    step
    y(m)=R*sind(n);
    x(m)=R*cosd(n);
    m=m+1;
end
plot3(x,y,z,'b-') % 3D visualization of helix

```

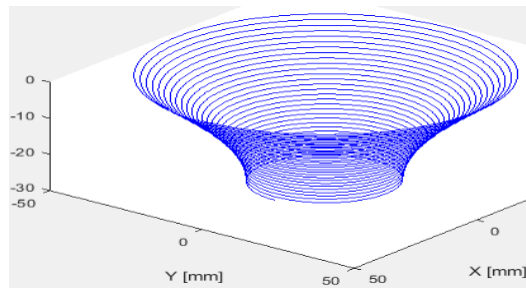


Figure 5: Isometric view of the hyperbola

The third sample part is the truncated pyramid. The parameters used to formulate this part are presented in Figure 6.

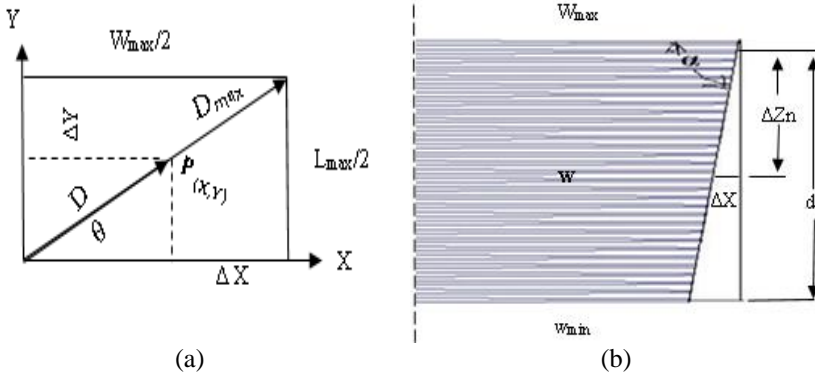


Figure 6: Parameters for the truncated pyramid; a) top view b) front view

The number of loops and values for the coordinate point Z are defined by using equations (2) and (5). Equations (10) – (14) are used to formulate the rest of the parameters for the truncated pyramid.

$$\Delta X = \frac{\Delta Z_n}{\tan(\alpha)} \quad (10)$$

$$D_{max} = \sqrt{\left(\frac{L_{max}}{2}\right)^2 + \left(\frac{W_{max}}{2}\right)^2} \quad (11)$$

$$D = D_{max} - \Delta X \quad (12)$$

$$X = D \cdot \cos(\theta) \quad (13)$$

$$Y = D \cdot \sin(\theta) \quad (14)$$

This section has attempted to provide the Matlab script that employed to define the spiral tool-path for the truncated pyramid. Figure 7 depicts the isometric view of the truncated pyramid.

```
clear
clc
dh=0.8;    %step depth used
a=45;     %angle of inclination of the pyramid
h=30;     %Depth of the pyramid
L=100; W=100;
```

```

X=L/2; Y=W/2;
R1=sqrt(X^2+Y^2); %diagonal length
N=h/dh; %Number of loops or contour
m=1;

for n=0:90:360*N %dividing one contour into 360
    angles
    z(m)=-((dh/360)*n);
    R=R1-(((dh/360)*n)/tand(a)); %diagonal at any
    intermediate depth
    y(m)=R*sind(n+45);
    x(m)=R*cosd(n+45);
    m=m+1;
end
plot3(x,y,z,'b') % 3D visualization of helix

```

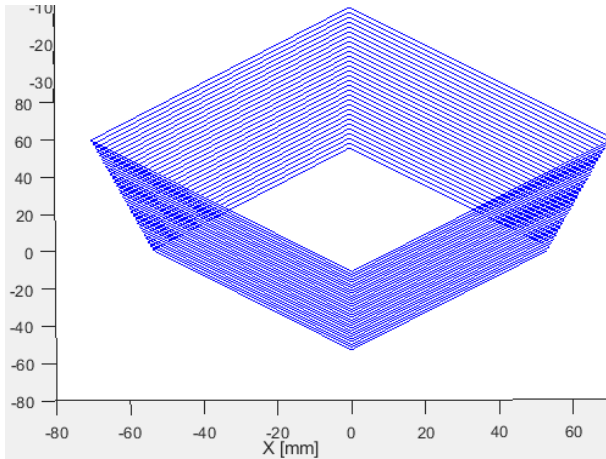


Figure 7: Isometric view of the truncated pyramid

### **Numerical Simulation**

The simulation of SPIF was conducted in ABAQUS to test the coordinate points created in Matlab. In the simulation, the displacement was defined by introducing the X, Y and Z coordinate points in the amplitude vs time data.

In the model, the sheet was fixed along its four peripheries. It defined as a deformable body and meshed with shell elements. The tool was defined as a rigid body. Figure 8 shows the deformed truncated cone, truncated pyramid, and hyperbola.

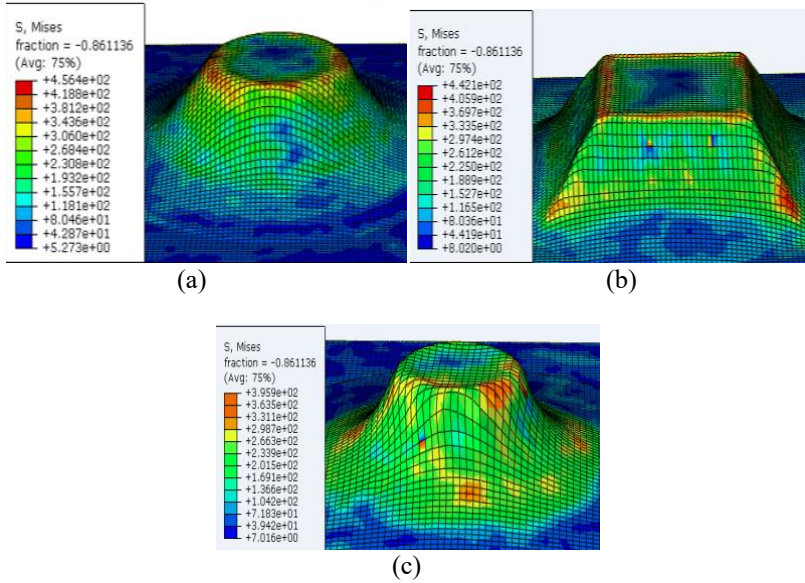


Figure 8: Numerical simulation of the; a) truncated cone, b) truncated pyramid and c) hyperbola

## Results and discussions

### Mixed String Generation

Table 1 provides a sample piece of coordinate points exported from Matlab by using the write table function and the mixed string created for a truncated cone. The mixed string is created by joining cell one to cell six by the “and” function. The mixed string data in Table 1 were input to create the G-code. By using the same procedure, mixed strings were created for the hyperbola and pyramid parts.

Table 1: Sample coordinate points exported from Matlab and mixed string

Part	Coordinate and Coordinate Points					Mixed String	
Cone	X	35	Y	0	Z	0	X35Y0Z0
	X	34.99	Y	0.61	Z	-0.002	X34.992Y0.611Z-0.002
	X	34.97	Y	1.22	Z	-0.004	X34.974Y1.221Z-0.004
	X	34.94	Y	1.83	Z	-0.007	X34.945Y1.831Z-0.007

### G-code Generation



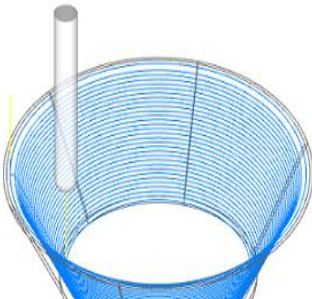
To change the mixed string into G-code, we must introduce it to the elements of the NC program. Preparatory and miscellaneous functions, coordinate values, feed rate, and spindle speed are the major elements of the NC program [10]. To accomplish this, a sample G-code was created from a truncated cone in Mastercam software (Table 2). The contour tool-path was used to define the tool-path. The preparatory and miscellaneous functions from the cone then introduced to the mixed string.

To generate the G-code, preparatory and miscellaneous functions from the sample G-code created from the truncated cone in Mastercam software were introduced at the start and end of the mixed string. Inserting block numbers, setting start and endpoints of the tool, define feed rate has done in SIMCO edit software. After that, the coordinate points have converted into G-code. The tool-path simulation of the G-code created from the Matlab script has shown in Table 3. Introducing the G-code to the CNC mill is required to form the sample parts.

## Conclusions

The aim of the current study was to create three-dimensional spiral tool path and convert it into G-code for the study of SPIF. This study set out to find a method for converting coordinate points created from Matlab script into G-code. This study makes a major contribution to show that coordinate points from the Matlab script can be converted into G-code. Prior to this study, it was difficult to convert coordinate points into G-code for the experimental investigation of SPIF. It is unfortunate that the study did not include the actual results of the experimental investigation gained after introducing the CNC mill. It would be interesting to compare this method and other methods used to create spiral tool path definition methods for the experimental investigation of SPIF.

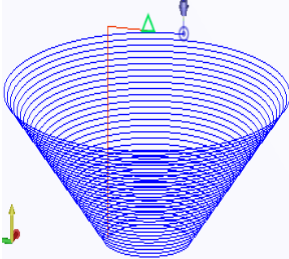
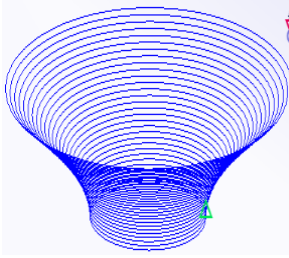
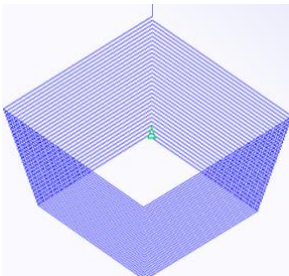
Table 2: Sample G-code for the truncated cone created in Mastercam

Position	G-code	Tool path simulation
Start	% N100 G21 N106 G0 G90 G54 X- N108 G43 H1 Z24.8 N112 G1 Z-.2 F1000.	
Intermediate	N114 X-33.113 Y-35.79 ----- -----	
End	N1258 M5 N1260 G91 G28 Z0.	

N1262 G28 X0. Y0.  
 N1264 M30  
 %

In the sample G-code, the preparatory and miscellaneous functions have found at the start and the end of the NC file. Whereas, the alphanumeric mixed string has found between the start and ends part of the NC file.

Table 3: Sample G-code and tool path simulation based on the proposed method

Part	G-Code	G-code Simulation
Truncated Cone	% N110 G21 N112 G0 G17 G40 G49 G80 G90 N114 T493 M6 N116 G0 G90 G54 X35 Y0 A0. S0 N120 G1 X35 Y0 Z0.1 F1000. N122 X35Y0Z0 N124 X34.992Y0.611Z-0.002 N126 X34.974Y1.221Z-0.004 N128 X34.945Y1.831Z-0.007 %	
Hyperbola	% N102 G21 N104 G0 G17 G40 G49 G80 G90 N106 T493 M6 N108 G0 G90 G54 X50.000 Y0 A0. S0 N110 G1 X50.000 Y0 Z0 F1000. N112 X49.988Y0.873Z-0.003 N114 X49.961Y1.745Z-0.006 N116 X49.918Y2.616Z-0.008 N118 X49.861Y3.487Z-0.011 %	
Truncated Pyramid	% N110 G21 N112 G0 G17 G40 G49 G80 G90 N114 T493 M6 N116 G0 G90 G54 X70.711 Y0 A0. S0 N118 G1 X70.711 Y0 Z0.000 F1000. N120 X70.711Y0.000Z0.000 N122 X0.000Y70.566Z-0.250 N124 X-70.422Y0.000Z-0.500 N126 X0.000Y-70.278Z-0.750 %	

**Nomenclature**

R <sub>i</sub> :	Maximum Radius	$\Delta R$	Radius change in a loop
R <sub>r</sub> :	Minimum Radius	$\beta$	Change in angle on the arc
R:	Radius at any depth	$\Delta X$ :	Change in the X
$\Delta Z$ :	Step depth	R <sub>n</sub>	Arc radius at any depth
d:	Depth of the part	D <sub>max</sub>	Initial diagonal length
N	Number of loops	D	Diagonal length at any depth
$\alpha$ :	Forming angle	W <sub>max</sub>	Top width
X,Y,Z	Coordinate Points	W <sub>min</sub>	Bottom width
$\theta$	Sweep angle	L <sub>max</sub>	Initial length
$\Delta r$	Change in radius		

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