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A METHODOLOGY FOR SIMULATION AND VERIFICATION OF TOOL PATH DATA FOR 3-AXIS AND 5-AXIS CNC MACHINING

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ABSTRACT

The main aim of using computer numerical control (CNC) technology for machining is to achieve better quality of machined part and intern increase the productivity of manufacturing operations. The NC toolpath data has the biggest effect on the machining time and accuracy of the machined surface obtained under given assumption that that we use an ideal machine tool and optimum cutting parameters for machining a workpiece on a CNC machine tool. In this paper, an approach for the simulation of tool path data for 3-axis and 5-axis machining has been introduced using Boolean subtraction approach using SolidWorksTM CAD package. The part modelling activities can be automated using macro in SolidWorksTM using Application Programming Interface (API). Thus in the developed NC toolpath simulator macro is developed for the verification of toolpath data for 3-axis and 5-axis machining operations for metal removal with ball end mill, flat end mill and toroidal end mill cutter shapes. The output from the simulated environment has been saved in STL format for easy comparison with the original part model which was also taken in STL format for the toolpath data generation. To verify the results generated from the simulator two methods namely visual graphical inspection and by use of ray tracing algorithm for determination of scallop height has been introduced. Two sculptured freeform part shapes to be machined with flat end mill cutter in 3-axis and 5-axis machining has been used to validate the working of the simulator macro as well as to verify the accuracy of input toolpath data.

Keywords: Simulation, 3-Axis and 5-Axis CNC Machining, Tool Path verification.

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1. INTRODUCTION

The engineering parts are described by the set of triangles which is known as Stereo Lithography (STL) format. This format is most widely used for tool path planning, generating tool path data. In machining operation using the triangulated model, a tool is made to pass over the tool path identifying the tool position and orientation. There is a need to verify the tool path generated from the triangulated model. There are different methods to verify tool path like machining the part or by NC simulator. Verifying the tool path using NC simulator is fast process as compared to the traditional method as shown in Figure 1.1.

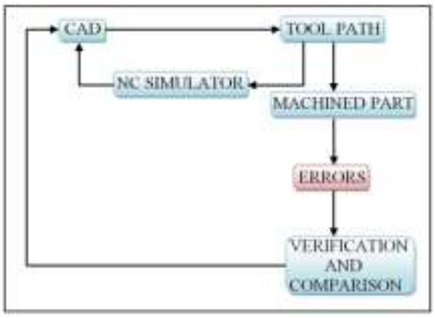

Figure 1.1 Need of developing simulator.

In this paper, for the verification of tool path, the tool path for 3-axis and 5-axis machining has been developed using algorithm developed by Duvedi et al. and the data has been provided by the authors [22]. An algorithm is developed in a commercially used CAD package (SolidWorks) using MACRO which can simulate the tool path for the user defined work piece with given parameters and the user defined tool. The visual and analytical verification of the simulation generated using the algorithm is performed using ray tracing methodology [6]. The idea of our method is at each tool position, boolean subtraction operation is performed.

2. LITERATURE REVIEW

The machining simulation is divided into two categories. The first one is geometric simulation and the second one is physical simulation. In geometrical simulation, the interference between the tool and the work piece can be graphically checked [20]. It is further used to check the undercut/ overcut of the work piece. In physical simulation, it is used to tell about forces required for cutting operation, vibration produced while machining, roughness of the machined surface, temperature of the machined surface and tool wear produced while machining.

In wireframe-based simulation, the shape of work piece which is machined and tool path displayed are in the form of wireframe. The simulation is fast and data structure is simple.

In solid modelling a complete 3D model is generated. The CSG ‘divide-and-conquer’ concept proposed by Su et al. [5] and Ho et al. [7] is the study of collision detection during the machining process. In this method CSG was used to represent the cutter and the work piece was represented by the cloud of more than 10,000 points, which was used to detect the penetration depth and the collision of tool in work piece. Mounayri et al. [2] developed an imitation system for 3 axis milling by ball end mill cutter which is based on solid modeller. The part was made by B-rep technique and cubic Bezier curves were used to show cutting edges of tool. Imani and Elbestawi [8] developed a simulation system by generating the swept volume of the cutter using sweeping technique or by using skinning technique. And then Boolean operation is performed on the work piece and the swept volume. Fleisig and Spence [13] stated that the machining simulation based on B-rep technique is more time consuming because of the increased part complexity. So to overcome this problem parallel processing techniques was used. Yip-Hoi and Huang [14] used a semi cylinder to represent the tool and the B-rep method is used to model the part. The solid modelling is used for the computation of tool and work piece intersection geometry. The cutter engagement is identified for each step of cutter during machining. Ferry and Yip-Hoi [17] extended Yip-Hoi and Huang [14] work to 5-axis machining. The parallel slicing methodology is used. This method generates the swept volume of the material removed by the cutter from work piece by Boolean operation. Lee and Lee [11] a smoother rendering along with a screening ability of the Z-map model in a 3-axis machining simulation. They used a local mesh method for the simulation process. Lee and Ko [10] stated that to enhance the Z-map model, the inclined sampling method was used. This technique is another version of anti-aliasing and it is used to increase the efficiency of simulation algorithm along with mesh rendering in computer graphics. In vector method, the facade of the part is represented by points. The direction vectors on these points are perpendicular to the surface. A direction vector keeps on extending till it intersects with another surface of the part or till it reaches the edge of the stock. A calculation of the meeting point of each direction vector and tool movement is made in order to simulate the machining process. If a vector intersects the envelope, then its length is reduced. In the simulation, each direction vector represents the edge of grass growing from the surface and the final length of the vector represents the amount of material removed at that point. Karunakaran and Shringi [15] developed a machining simulation in which the formation of the part and amendment in the part was done by octree method. Then for visual verification, optimisation and animation of the machining simulation is done by B-rep method. Dyllong and Grimm [16] stated that the nodes of octree are divided into eight nodes. These nodes are compared with the cuboids. Each node contains the objects of the part. Every node of the octree is checked whether it is fully or partially occupied or the node is empty. Lee and Nestler [18] stated that the machining of the product is the material removal process with a geometry defined cutting tool. In order to verify the tool path, the tool swept volume (SV) is continually subtracted from the raw stock in the virtual environment during simulation. Sullivan et al. [19] stated that the boundary representation (B-rep) is used by the solid modelling based simulators in order to show case the milled work piece and in order to perform the Boolean subtraction operation between a work piece and swept volume of the tool between two positions. In simulation process generation of swept volume of tool is required. Sheltami et al. [3] stated that the simulator developed use the swept volume of the cutter for the milling operation and then perform the Boolean operation between the work piece and swept volume of the tool. This technique is based on recognizing the generating curve along the tool path, then to make a solid from these generating curves to form a swept volume of the cutter. The swept volume for the radius end mill cutter with the help of generating curve is as shown in Figure 2.1.

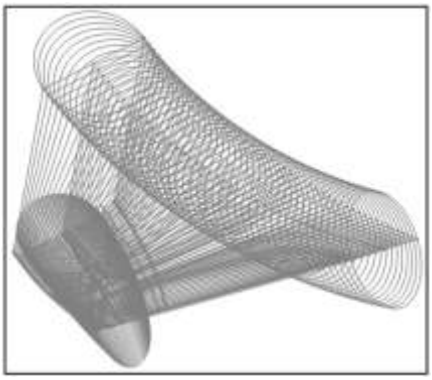

Figure 2.1 Swept volume of radius end mill cutter.

Roth et al. [4] stated that the tool swept volume is generated using the space curves. A curve is identified on the tool surface for a given tool location. This is the impression of the tool on the surface to be machined. The imprint space curve is identified for each tool location and volume swept by the tool is generated. S. Mann and S. Bedi [12] extended the imprint method for finding the swept volume for the surface swept by the tool for the machining of the curved surfaces. The grazing points are calculated on surface of revolution and with the help of these grazing points, grazing curve is generated for the cutter.

The verification of the simulated model is verified using ray tracing methodology. The comparison is performed between the data generated from the ray tracing methodology of the original STL model and the simulated STL model. D. Badouel [1] proposed the study to find the intersection between the rays and triangles. In his study he used the barycentric co-ordinates to find the intersection between the line and triangles. Segura and Feito [9] proposed the algorithm to test the intersection of ray-triangles. They proposed the study in which no errors were involved. They used the sign of triangles in the algorithm to find the intersection. Where there is intersection the point of intersection can be calculated. The complex calculations are not there in this algorithm, so the results computed are very much precise and accurate.

3. PROPOSED IDEA FOR MACHINING SIMULATION FOR 3-AXIS AND 5-AXIS MACHINING

In our work a computer program in visual basic for application is created in API SolidWorks and it can be used for the automation to generate the model in SolidWorks. This automation is used for the simulation of tool path in SolidWorks. The macro is created for the development of simulator. The inputs required for the macros for NC simulator are: 1. Raw stock, 2. Tool shape 3. Tool path, 4. Type of machining

For the simulation process the initial task is to select the type of machining for which the simulation of the tool path has to be performed. Corresponding to that the tool path is taken in excel file. In case of 3-axis machining there is a need of cutter location data and for 5-axis machining there is a need of second point on tool axis along with the cutter location. The tool path data required for 3-axis and 5-axis machining is shown in Figure 3.1.

Then enter the parameters required for raw stock and generate raw stock. The raw stock is generated in positive X and Y axis and machining will take place in negative Z direction. After that select the type of tool that is required for machining process. Three types of tools are mainly used for machining process are radius end mill cutter, flat end mill cutter and ball end mill cutter. The flat end mill cutter and ball end mill cutter are derivative of radius end mill cutter. In case of radius end mill cutter $R2 > R1$. Whereas in case of ball end mill cutter $R1 \rightarrow R2$ and in case of flat end mill cutter $R2 \gg R1, R1 \approx 0.001\ mm.$ $R2$ is tool radius, $R1$ is fillet radius or radius of pseudo insert circle and L is the length of tool. The tool shapes and the zoom in sections of the variations of tool are shown in Figure 3.2. If the radius of pseudo insert circle of radius end mill cutter is approaching zero, then flat end mill cutter is considered and if it is equal to tool radius then ball end mill cutter is considered.

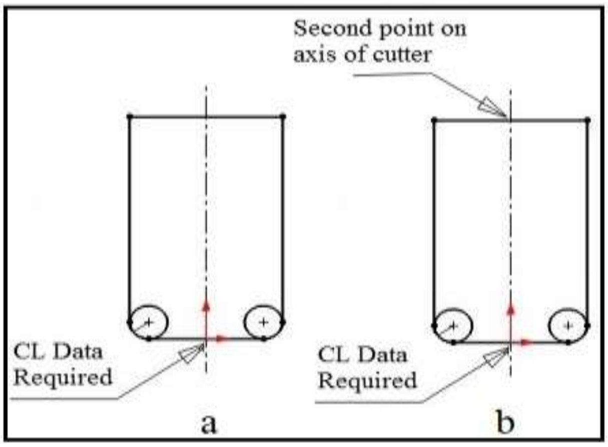

Figure 3.1 Data required in Excel File for 3-axis and 5-axis machining respectively.

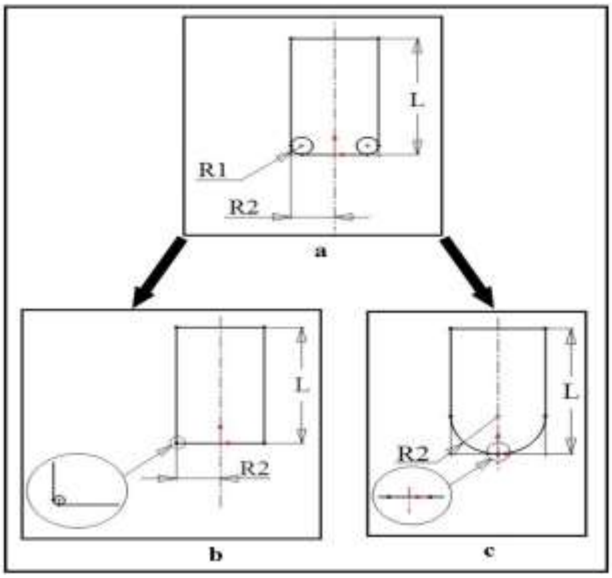

Figure 3.2 Tool Shapes: (a) Radius end mill, (b) Flat end mill and (c) Ball end mill cutter.

Start the simulation process. The simulation of the machining process is done using boolean subtraction approach and solid sweep approach. The solid sweep approach is faster than boolean subtraction approach but this methodologies fails for the freeform sculptured surfaces. In boolean subtraction approach the tool is oriented about the axis generated and positioned at the CL point. The boolean subtraction operation is performed to subtract the tool from the raw stock to get the final output. The pseudo code for 3-axis and 5-axis machining simulation is shown in Figure 3.3. A radius end mill cutter is shown in Figure 3.4 as it moves during a 3-axis and 5-axis NC machining simulation. The tip of the cutter moves along a prescribed cutter location (CL) trajectory in case of 3-axis and 5-axis machining simulation as shown in Figure 3.5.

```
\\ Pseudo code for 3-axis and 5axis machining simulation
i, x1, y1, z1, x2, y2, z2 = integers      \\ Define variables
Part = swApp.NewDocument                  \\ Open new part
Part = swApp.ActiveDoc
Excel.Application                         \\ Open excel sheet
swExcel.ActiveSheet
InsertPart (raw_stock.sldprt)             \\ Insert raw stock
Insert3DSketch                            \\ Make 3D sketch
Do While exSheet (i, 1) < > ""
                x1 = exSheet (i, 1)
                y1 = exSheet (i, 2)
                z1 = exSheet (i, 3)
                x2 = exSheet (i, 4)
                y2 = exSheet (i, 5)
                z2 = exSheet (i, 6)
                CreateLine (x1, y1, z1, x2, y2, z2)
        i = i + 1
Loop
i =1
Do While exSheet (i, 1) < > ""
InsertPart (tool.sldprt)                  \\ Insert tool shape
AddMate                                   \\ Position the tool
Select "AXIS"
Select "LINE"
Coincident                                \\ Coincident constraint between axis and line
Select "PLANE"
Select "POINT"
Coincident
If i = 1 Then
Select "raw_stock"
Else
Select "CombineName"
End If
Select "tool"
InsertCombine                             \\ Boolean operation
i = i  + 1
Loop
SaveAs (5axis_simulation.sldprt)          \\ Save
```

Figure 3.3 Pseudo code for 3-axis and 5-axis machining simulation.

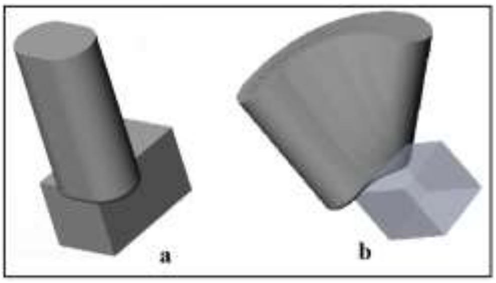

Figure 3.4 Radius end mill cutter moving through work piece (a) 3-axis, (b) 5-axis.

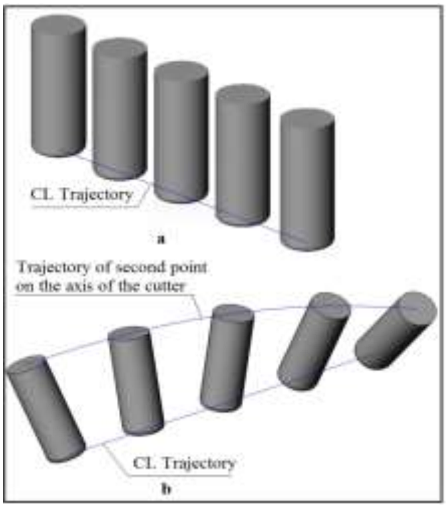

Figure 3.5 Radius end mill cutter moving through space along CL trajectory (a) 3-axis, (b) 5-axis.

4. VERIFICATION

The most important thing is the verification of the tool path generated from the part and the final output generated by simulation process from this tool path. The visual and analytical verification of the tool path is possible [21]. The final output generated after the simulation process is saved in the *.sldprt format and *.stl format for visual and analytical verification respectively. The verification methodology is same for the 3-axis and 5-axis machining.

For the visual verification of the simulated part, compare the part formed by the simulation process and the part from which the tool path has been generated. Open the new assembly in SolidWorks. Insert the machined part at the default position in the assembly from which the tool path has been generated. Similarly insert the final output generated after the simulation process at the default position. The output thus can be used for visual verification of the tool path.

For analytical verification STL file is generated for the simulated part. The ray tracing of the simulated part is done. The data thus generated is compared with the ray traced data of original part from which tool path is generated. The algorithm to find the comparison between the two is as discussed.

1. Equation of line: $\boldsymbol{T(u) = T_1 + u\,(T_2 - T_1)}$
2. Equation of triangle: $\boldsymbol{P(s) = P_1 + s(P_2 - P_1) + t(P_3 - P_1)}$
3. At the intersection of line and triangular surface, equate the two equations.

$$\boldsymbol{T_1 + u\,(T_2 - T_1) - P_1 + s(P_1 - P_2) + t(P_1 - P_3) = 0}$$

$$\boldsymbol{u\,(T_2 - T_1) + s(P_1 - P_2) + t(P_1 - P_3) = P_1 - T_1}$$

The above equation can be written as: $\boldsymbol{u\,(A) + s(B) + t(C) = \Delta}$

The above equation can be written in matrix form

$$\begin{bmatrix} \boldsymbol{T_2 - T_1} \\ \boldsymbol{P_1 - P_2} \\ \boldsymbol{P_1 - P_3} \end{bmatrix} \begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{s} \\ \boldsymbol{t} \end{bmatrix} = [\boldsymbol{\Delta}]$$

Where $\boldsymbol{T_2 - T_1 = A, P_1 - P_2 = B, P_1 - P_3 = C}$

The above equation can be written as

$$\begin{bmatrix} \boldsymbol{A_x} & \boldsymbol{A_y} & \boldsymbol{A_z} \\ \boldsymbol{B_x} & \boldsymbol{B_y} & \boldsymbol{B_z} \\ \boldsymbol{C_x} & \boldsymbol{C_y} & \boldsymbol{C_z} \end{bmatrix} \begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{s} \\ \boldsymbol{t} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Delta_x} \\ \boldsymbol{\Delta_y} \\ \boldsymbol{\Delta_z} \end{bmatrix} \qquad \textbf{(1)}$$

1. Find u, s and t using equation (1).
2. If $\boldsymbol{0 \leq u, s, t, s + t \leq 1}$ only then the solution is valid.
3. Repeat the above algorithm for all the triangles.
4. The ray traced data contains the co-ordinate values of each cutter location for the machined part. Similarly find the co-ordinates for the simulated part. Find the difference in the co-ordinates for each cutter location. If the difference is coming out to be positive then there is an overcut and if the difference is coming out to be negative then there is an undercut.

5. RESULTS

The actual tool path for the parts is generated from the STL file of the part. The tool path is imported into the excel sheet. The input parameters used for simulation are given in Table 5.1. The original part from which the tool part is generated is given in Figure 5.1.

Table 5.1 Input parameters for machining simulation

Length of raw stock	25mm
Width of raw stock	50mm
Thickness of raw stock	40mm
Shape of tool	Flat end mill tool
Radius of tool	3mm
Length of tool	10mm

The visual verification for the given part 1 and part 2 using 3-axis and 5-axis machining simulation is shown in Figure 5.2.

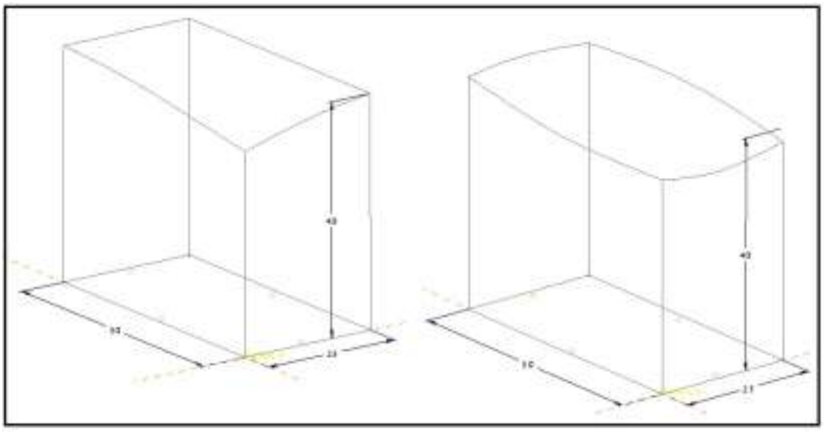

Figure 5.1 Machined part 1 and part 2.

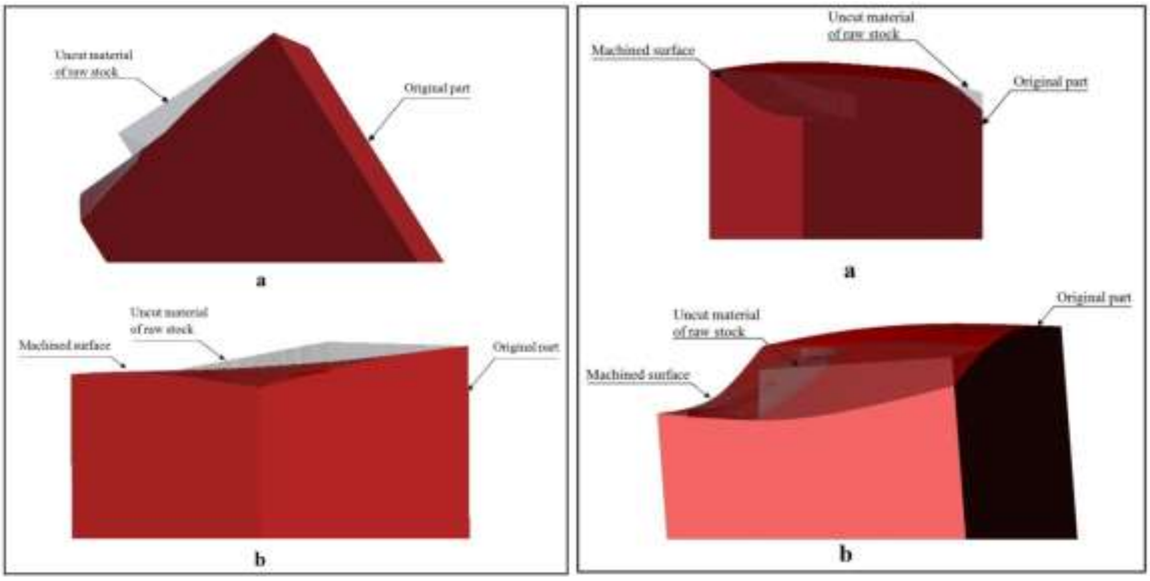

Figure 5.2 Visual verification of part 1 and part 2 (a) 3-axis and (b) 5-axis machining simulation.

The analytical verification for the two parts using the ray tracing methodology is discussed here. The ray intersection data (x, y and z) are calculated in the feed forward/ tool motion direction with the given increment and in the side step direction with the given increment. The ray is traced from 0 to 4mm in x direction and from 10 to 30mm in y direction. The ray tracing of the part with the given parameters is shown in Figure 5.3.

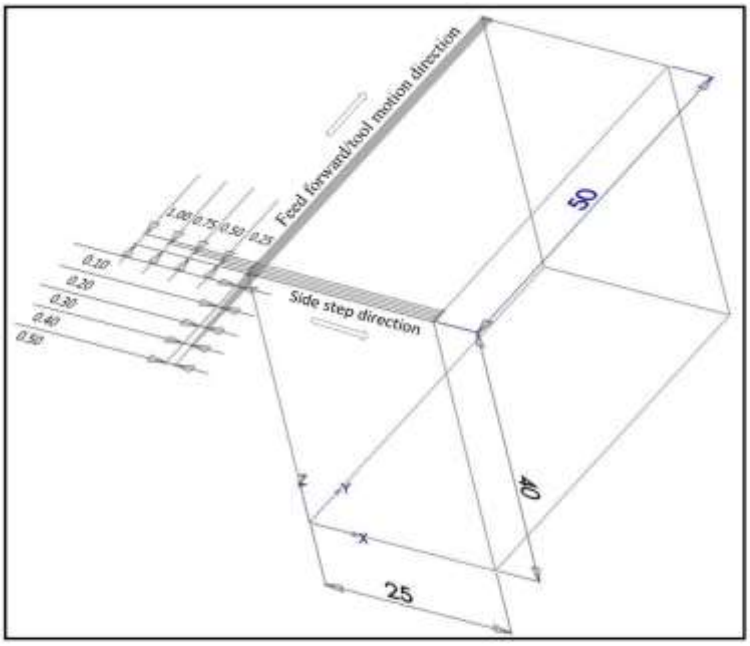

Figure 5.3 Ray tracing of part.

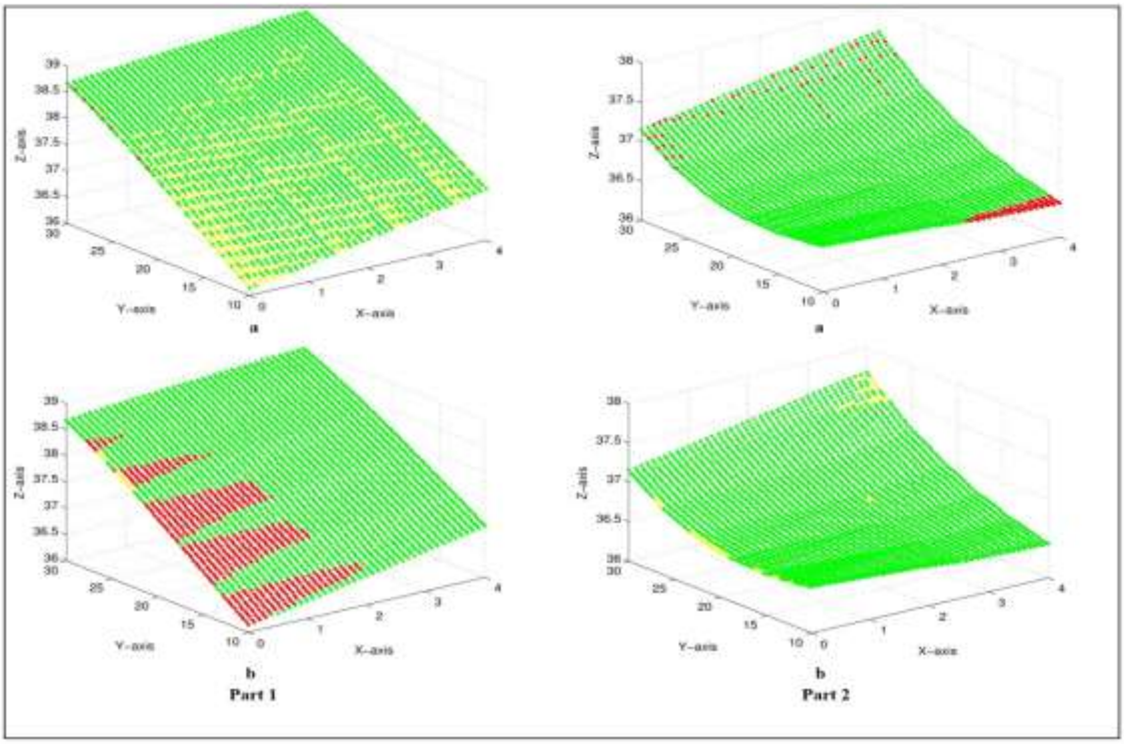

Figure 5.4 Comparison of original machined part and simulated part (a) 3-axis and (b) 5-axis.

The 3D plots for 3-axis and 5-axis machining are formed which is used to represent the undercut/ overcut of the simulated part. The yellow color represents the undercut; red color represents the overcut and green color within the tolerance region of the simulated part. The tolerance acceptance region for the simulation is taken from -0.1mm to +0.1mm. The feed forward step increment is taken as 0.1mm and the side step increment is taken as 0.25mm. The comparison is shown in Figure 5.4.

These variations are because of that the tool path is generated for 1mm feed forward and 1mm side step distance for 3axis machining and 1mm feed forward and 3.5mm side step distance for 5-axis machining. There are some stairs cases which will be generated from one tool position to next tool position whereas in actual machining those steps are not there. In this overcut values are there is primarily because of Boolean operation and left out stair steps further because we have tried to compare the original STL model with the output of simulated part again taken in STL format with 0.03mm chord height. So there can be some errors found using ray tracing comparison at given x y location for z height of actual part and simulated part. As the chord height for original part is 0.05mm and for the simulated part the chord height is taken as 0.03mm. The errors in the tool positioning with respect to the original part is of the magnitude ±0.05mm, they are expected. Similarly in ray tracing of simulated part the errors in the tool positioning is of magnitude ±0.03mm is expected.

The 2D plots are formed for the study of scallop height in 3-axis and 5-axis tool paths. The plots are formed for given y values against the x and (z2-z1), where z2 is the z values of the ray traced for the simulated part and z1 for the original part. The ray is traced for the original part and the simulated part with the ray intersection data for x=0 to 4mm and y=10 to 30mm. The feed forward step increment is taken as 0.1mm and the side step increment is taken as 10mm. Plot between the original part and 3-axis simulated part at y=10, 20 and 30mm is shown in Figure 5.5 and for 5-axis shown in Figure 5.6.

The graphs shown in Figure 5.5 and 5.6 have been plotted for x-axis direction (perpendicular to across the tool path direction, which is y-axis) for part 1 for 3-axis and 5-axis machining and in Figure 5.7 and 5.8 for part 2. A good estimate of scallop height can be made from the uncut material by comparing the side step direction distance with the difference in z height of original STL file and simulated STL file. The errors are there for each side step as explained for the 3-D plots. The graph shows that the error for each side step is not more than the 0.2mm which is in the permissible range. In Figure 5.6 and 5.8, the side step in 5-axis is more as compared to the tool path for 3-axis machining. The tool permits to be close to the surface of work piece so scallop height is same. The scallop is smooth and this is not more than 0.2mm.

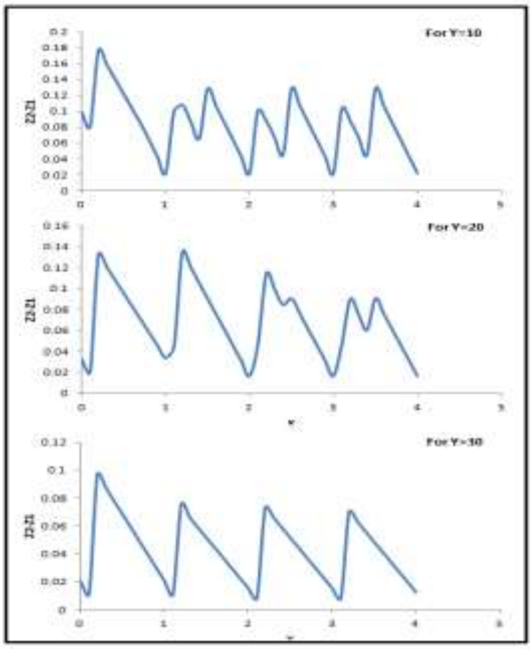

Figure 5.5 Plot for the scallop height for 3-axis simulated part 1.

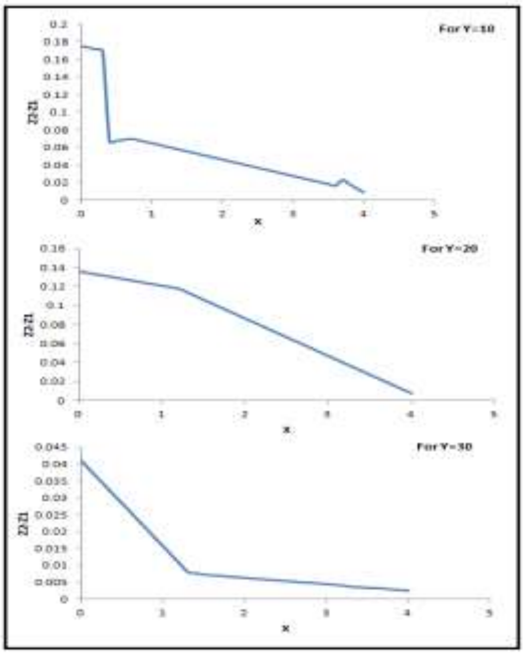

Figure 5.6 Plot for the scallop height for 5-axis simulated part 1.

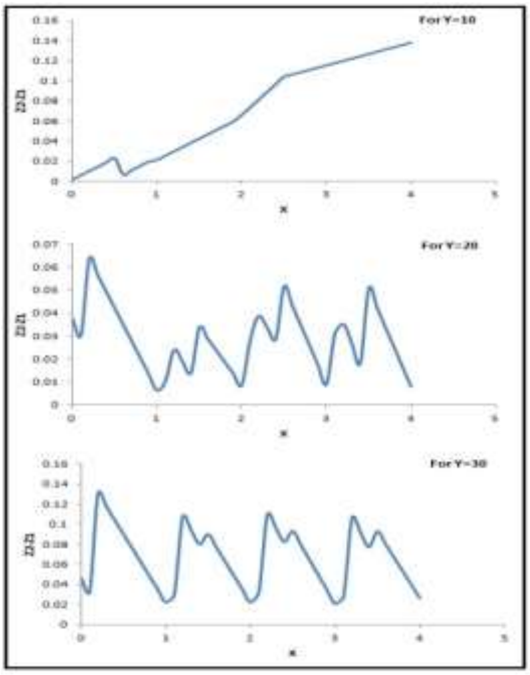

Figure 5.7 Plot for the scallop height for 3-axis simulated part 2.

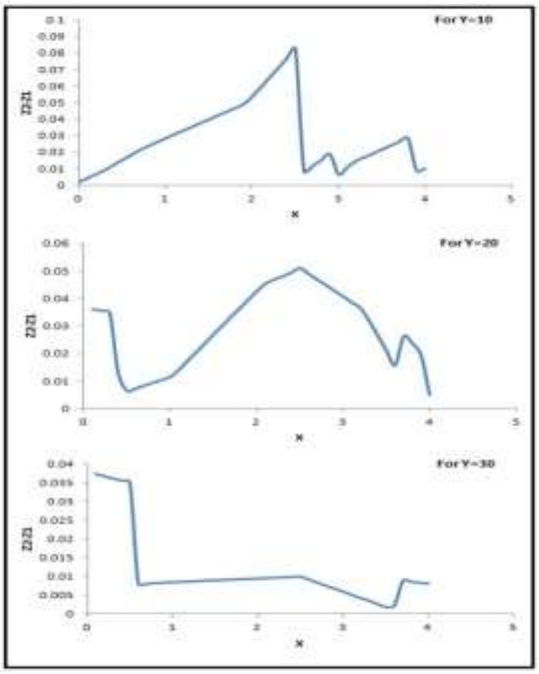

Figure 5.8 Plot for the scallop height for 5-axis simulated part 2.

5. CONCLUSION

The boolean subtraction method presented in this work can be used to simulate the given tool path for 3-axis and 5-axis machining. The verification of the tool path is possible without the loss of data. In the developed macros without incurring the additional errors accumulated because of actual machining and inherent errors of error measurement procedure. But there are some other formats of inaccuracies found during our process which is like stair steps, they show the overcut. The visual and analytical verification of the simulated part is done. For the analytical verification the ray tracing methodology is used for the verification of simulated part with the original part. The results generated from the simulator are valid.

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