Tool Path Optimization of Contouring Operation and Machining Strategies for Turbo Machinery Blades

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Abstract— **Today many industries use CNC machines for production of turbo machinery components like turbine blades, impellers, rotors, propellers etc. Turbine blades are complex shapes and difficult to machine on CNC. Contouring operations are generally used for this purpose. This paper presents optimization of toolpath for turbine blades in vertical machining centre (VMC). Toolpath optimization of turbine blade using MasterCAM® software results in reduction of machining time. Different contouring toolpaths are simulated in MasterCAM® prior to machining of turbine blades. Cutting Parameters used for machining are spindle speed, feed, tool diameter, plunge-rate, and depth of cut.**
Most of the research work is focused on cutter path generation with the main aim on reducing total cycle time. Both productive time and non-productive times (airtime, tool change time) are considered for optimization. Different toolpath generation methods are studied to select the best one to find out optimized cycle time. Different contour toolpaths being simulated are 2D, chamfer 2D, Ramp, Remachining and Oscillating. The objective of simulation is to generate the shortest tool-path for contouring operation. Actual machining is done to validate the software simulation time. Experimentation reveals that zigzag toolpath is more favorable than any other strategies for the machining of turbine blade for minimum cycle time. Ramp contour toolpath is more favorable than any other toolpaths.

Keywords— **toolpath, optimization, simulation, strategies**

I. INTRODUCTION

Geometrical complexity and difficulty in machining of turbine blades has been challenges forth manufacturing industries. Now a days, many industries use CNC machines to shape turbomachinery components. Simultaneously use of different modeling & simulation softwares like MasterCAM®, Pro-manufacture and Unigraphics NX etc. is very common. MasterCAM® is an effective tool to generate, execute and thereby simulate tool paths. Effect of change in parameters on machining time can be realized in short time. The embedded postprocessor generate NC codes compatible to different makes of CNC machines.

While simulating machining, tool movements on workpiece decides productivity. In complex machining tasks, cutting time, air time, tool changing time, traverse time and retract time constitute major part of total machining time. But effective cutting time is of major concern. Hence, tool movements can be studied in terms of toolpaths.

There are two types of toolpaths - contour-parallel and direction-parallel. The contour-parallel toolpath comprises of a sequence of contours that are parallel to the boundary of the 2D cross-section. In direction-parallel toolpath path segments are generated along a specific direction [8]. Decide a toolpath which results in less machining time or the short path length. There are three types of the direction parallel toolpath. (1) Unidirectional tool path, (2) pure zigzag tool path, and (3) smooth zigzag tool path with the contour-parallel toolpath.

Toolpath optimization and the development of minimum cycle time based on CAD/CAM simulation is undertaken by many researchers. CAD/CAM software gives machining time automatically based on the different cutting strategies. Among these different strategies shortest time is used for further machining operations. By using this technique significant amount of machining time is reduced and optimized tool path is obtained. But most of the CAD/CAM systems are not capable to provide machining time automatically similar to MasterCAM® software.

The cycle time can be reduced by selection of proper tool path strategy and modifying some of the design parameters of cycle time. Tool starts at the origin, navigates on toolpath and finally returns back to the origin, where the next tool replaces it. The tool can move continuously within a toolpath without lifting but it has to lift while going from one cell to another resulting in non-productive time. Hence in order to minimize the non-productive time, all the toolpaths for a tool must be connected with the minimum possible length. [13]

The manufacturing of turbine blade consists of automatic toolpath generation for multi axis CNC machine. This involves presetting and selection of cutting tool, its position as well as flawless navigation of tool for avoidance of collision.

II. MACHINING STRATEGIES

A variety of machine tools are suitable for blade machining viz. 3, 4, or 5-axis machines. 3-axis CNC machines are seldomly used for modern blade machining operations due issues of degrees of freedom on drives. They can only effectively produce simplest shapes and geometries. However,

such machines are still widely used and are found profitable. 4-axis machining is more common, particularly in older machines which have been upgraded with NC-programming capability. But the modern trend is towards 5-axis machines, which allow maximum flexibility and versatility while still using standard cutting tools. [18]

The choice of overall machining strategy is important, and will greatly influence the subsequent machining parameters. These strategies fall into two classes:
1) Machining with one (or more) individual machining centre(s)
2) Machining with a dedicated machining cell

Deciding which strategy is best in a particular situation depends on numerous factors, including:
- The different types and size of blade
- The design of the blade
- The number of blades of each sizes
- The machining operation involved
- The process flow
- The CAD/CAM system
- The operating performance

III. TOOLPATH GENERATION METHOD

The toolpath generation method is to compute a sequence of cutter location points from the design surface. Toolpath generation methods are classified as CC-based method and CL-based method depending on the type of toolpath generation surface. [16]

A. CC-Based Method

Cutter Contact (CC)-based method, toolpaths are generated by sampling a sequence of Cutter Contact-points from the part surface then each CC-point is converted to a cutter location (CL)-point. In general this method can be classified in to three main categories. These are normally called as the conventional tool path generation methods.

1) Parametric Method

Computes the toolpath figure in the parametric domain and the maps it back to the part surface. The surface is mapped into the parametric domain. By observance one of the parameter constant, the iso-parametric curves generated are use as a guide for the toolpath. Iso-parametric machining, one of the earliest techniques, involves machining along Iso-parameter lines.

2) Drive Surface Method

Drive surface method computes tool paths by intersecting the design surface with a sequence of plans called drive surfaces. The turbine blade generated by intersecting are then used to generate accurate toolpath. Intersecting planes are parallel then known as iso-planar machining. Direction of the intersecting plan can be changed to achieve most select condition of machining.

3) Guide plane Method

Guide plane method plans the toolpaths first on a 2D plane and then maps it back to the design surface. For 3-axis milling, the plane perpendicular to the tool axis is mainly used as the guide plane. The major strength of this method is the region to be cut on the part surface can be considered during planning the toolpath layout on the guide plane.

4) Isoplaner Toolpath Method

In this method parallel planes are created to generate intersection curves with the part. These curves are used guide the cutting tool's movement. This method while maintaining a uniform path, does not take into consideration the topology of the machine part.

B. CL-Based Method

In this method the CL-surface is used as a path generation surface. CL surface has to be first generated from the design surface. This method has been employed in the current work. The offset surface is first generated from the design surface and tool paths are considered on the offset surface. Zigzag tool paths, parallel to each other, are designed according to the machining parameters. Their work to a reduce cutter location data.
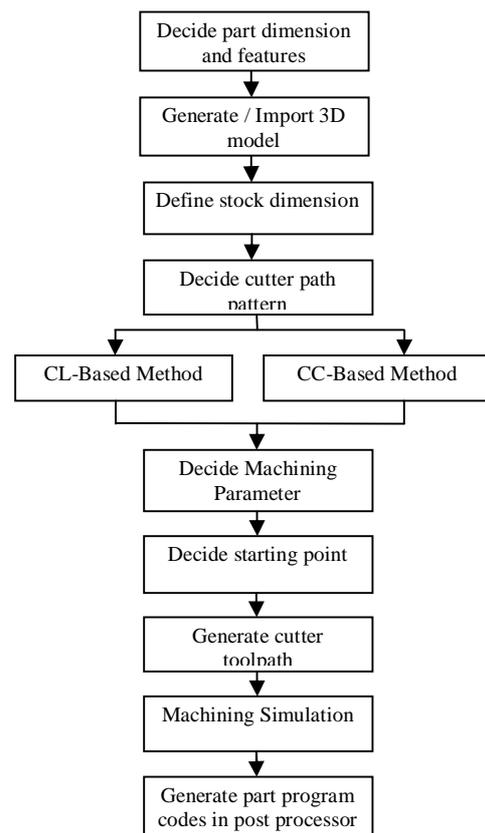
Fig. 1 Flowchart for contour toolpath generation

IV. OPTIMIZATION TECHNIQUES

Today many integrated computer-aided design and manufacturing (CAD/CAM) systems are available capable of generating machining toolpath for various operations. In addition these systems often do not generate optimum toolpaths in CNC machining operations. For this optimization of toolpath the proposed techniques would be apply on machining operation. The optimization techniques of toolpath are discussed below:

1) Multiple cutting tool

There are two or more cutting tool taken minimum machining time. Multi tool cutting tool is use to maximize machining time with respect to single cutting tool.

2) Cutting parameter

There are different Cutting Parameters such as spindle speed, feed, tool diameter, plunge-rate, and depth of cut. Variation of cutting parameter gets comfortable results for optimization.

3) Different contour toolpath

Different contour toolpaths like 2D, chamfer 2D, Ramp, Remachining and Oscillating minimum cycle time and airtime are simulated for machining turbine blade. There are two main tool path patterns commonly used in 2.5D end milling operations: direction parallel tool paths and contour parallel tool paths. The relative merits of direction parallel and contour tool According to a recent study, the best tool path depends upon the geometry of the part, the machining characteristics, and cutting conditions. The contour parallel tool paths are known to be coherent as the tool is always in contact with the material and thus reduces idle time spent in lifting, positioning, and plunging of the tool. Also, they maintain the consistent use of either up-cut or down-cut milling strategy. Contour parallel tool paths are, therefore, widely used as cutting tool paths.

Direction parallel tool paths, also commonly referred to as zigzag or zig machining, are not preferred for features with hard boundaries because cusps are left behind along the hard edges during rough machining. The removal of these cusps requires an extra pass thus increasing the total tool path length.

4) Reduce Airtime

Airtime is defined as the time of toolpath when material is not removed at machining. The airtime is considered from finishing of first cut to starting of second cut. So airtime is necessary to reduce for optimized the machining time.

5) Retract

Retract use for second pass of toolpath after completion of one pass during machining. Its benefit is that is no damage regarding to clamp. Taken minor retract gives reduce in length and time. But choose option keep tool down, when selecting parameter in MasterCAM®. There is no reduction time regarding to retract.

6) Plunge rate

Plunge rate is defined as the feed when movement of tool is down in depth at machining operation. Plunge rate is selected with respect to feed rate according to standard.
Plunge = ½ or ¾ feed

V. MASTERCAM® SOFTWARE SIMULATION TECHNIQUES

In this work the MasterCAM® is used to simulate machining of turbine blade. Different contouring toolpaths are available in this simulation tool. However, the main goal of this simulation step is to generate the shortest tool-path for contouring operation. Throughout experiments, cutting parameters, blade geometry, first point and end point of tool movements are same for all strategies of cutting. Thereafter, for each simulated strategies, MasterCAM® generates NC codes through postprocessor.

C. Selection of cutting parameter

Cutting parameter is selected from standard data of machining. Cutting parameter are also taken from "cutting speed software" which is shown in table I. This software gives spindle speed and feed rate with respect to work piece material, tool material and tool diameter.

The shape of aerofoil of Eiffel 385 (S.T.Ael) blades is indicated in the figure 2.

TABLE I.   CUTTING PARAMETERS

Sr. No	Operation	Tool Dia.	Spindle Speed (rpm)	Feed (mm/min)	Material
1	Pocket (facing)	10	1225	367	aluminum
2	Contour	6	1642	246	aluminum
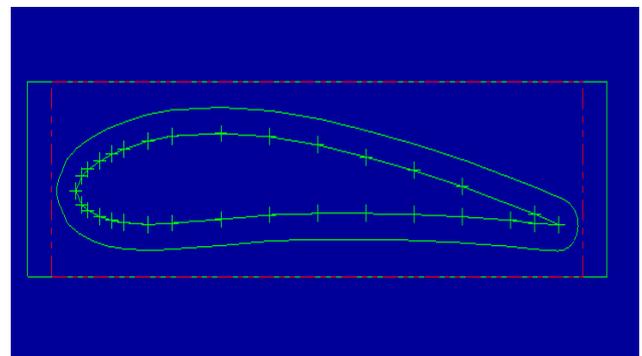
Fig. 2 Eiffel 385 (S.T.Ael) blade [1] aerofoil shape turbine blade geometry in MasterCAM®

Fig. 3 Turbine blade machining: pocket (facing) operation
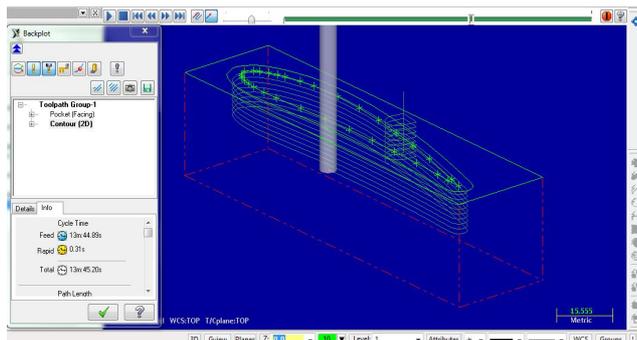
Fig. 4 Turbine blade machining: Contouring operation

The coordinate are taken from the website [1] of NACA for the shape of aerofoil. The geometry of blade is created by applying MasterCAM® software with blade coordinates. Same way complex geometry can be created.

Figure 3 and 4 shows respectively pocket (facing) toolpath and contouring operation back plot described in MasterCAM® software. Back plot gives toolpath length and machining time. It is also to simulate the complete machining.
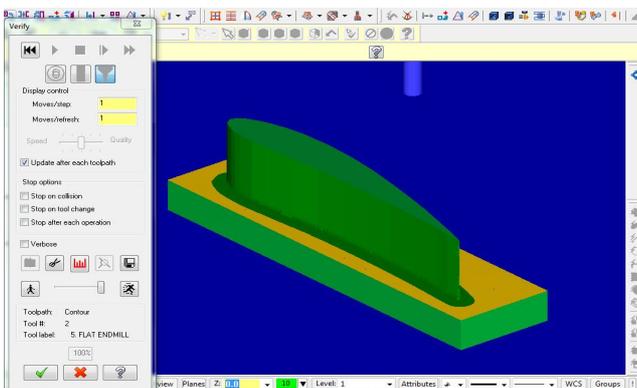
Fig. 5 3D view of simulated turbine blade

Figure 5 shows verification of turbine blade in MasterCAM® software. One can see a 3D animation of the cutting blade and can verify whether some material left or not.
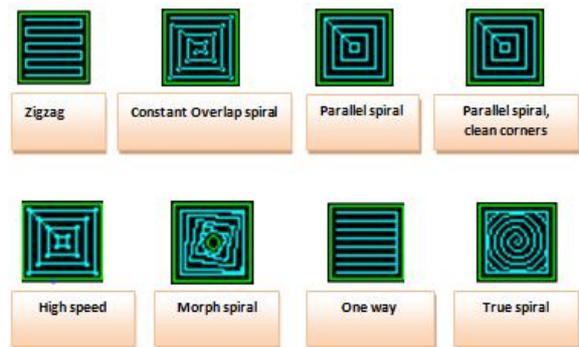
Fig. 6 Various Toolpaths in MasterCAM® Software

The experiments can be done accordingly to the machining cutting path strategies. These are seven cutting path strategies are being used for this project. The machining of cutting methods are shown in figure 6.

D. Optimization

MasterCAM® software simulation times of all toolpaths are described in table II. Zigzag toolpath gives minimum time which is 30m 45.14sec compare to other toolpath. Here morph spiral toolpath gives maximum machining time which is 38m 24.73sec.

TABLE II.   SOFTWARE SIMULATION RESULTS

Sr. No	Toolpath	MasterCAM® Software Simulation Time
1	Zigzag	30m 45.62sec
2	Constant Spiral	32m 33.44sec
3	Parallel Spiral	32m 18.11sec
4	Parallel Spiral, Clean Corners	33m 40.39sec
5	Morph Spiral	38m 25.21sec
6	One way	33m 13.28sec
7	True Spiral	37m 26.40sec

E. Contour Toolpath

Simulation results of contour toolpath for 6mm and 10mm tool diameter are described respectively in table III & IV. Ramp contour toolpath gives minimum machining time which is 29m 48.87sec and Remachining contour toolpath gives maximum machining time which is 30m 45.62sec.

TABLE III.   SIMULATION RESULTS OF 6MM TOOL DIA

Sr No	Toolpath	Soft. Simulation Time (min)	Pocket (Facing) time	Contour time
1	2D	30m 45.62sec	15m 3.63sec	15m 41.99sec
2	Ramp	29m 48.87sec	15m 3.63sec	14m 45.24sec
3	Remachining	30m 45.62sec	15m 3.63sec	15m 41.99sec

Ramp contour toolpath gives minimum machining time which is 25m 32.87sec and Remachining contour toolpath gives maximum machining time which is 30m 45.62sec for

10mm tool diameter. The machining time of pocket (facing) toolpath is constant and the machining time of contour toolpath is varying.

Figure 6 shows aluminium stock material (110mm x 30mm x 30mm). Various toolpaths are simulated in the MasterCAM® software to make such a turbine blade. Post processor brings out the toolpath program through the process of simulation of toolpath. This program is fed into VMC machine.

TABLE IV.   SIMULATION RESULTS OF 10MM TOOL DIA

Sr. No	Toolpath	Soft. Simulation Time (min)	Pocket (Facing) toolpath	Contour toolpath
1	2D	26m 57.05sec	15m 3.63sec	11m 53.41sec
2	Ramp	25m 32.87sec	15m 3.63sec	10m 29.24sec
3	Remachining	30m 45.62sec	15m 3.63sec	11m 53.41sec

VI. EXPERIMENTAL MACHINING SET-UP

Manufacturing of blade is done on 3-axis vertical milling centre.

Fig. 6 Aluminium stock material

The program is run continuously in the machine and machining occurs automatically. The cutting tool removes material according to the programmed fed. The first operation is pocket (facing). A 10mm diameter flat end mill tool is used to remove material speedily in pocket (facing) operation. The final turbine blade shape of achieved by contouring operation in which 6mm diameter tool is used to get absolute finishing.

Fig. 7 Machined Turbine blade

The figure 7 indicating turbine blade is manufactured completely in 3-axis vertical machining centre (VMC) machine.

F. Optimization

Turbine blades are produced for each toolpath as shown table V. Zigzag toolpath require minimum actual machining time of 31m 37sec compared to other toolpaths. The Morph spiral toolpath gives maximum machining time of 39m 38sec.

TABLE V.   EXPERIMENTAL MACHINING TIME FOR VARIOUS TOOLPATH

Sr. No	Toolpath	Experimental Machining Time (min)	Percentage (%)
1	Zigzag	31min 37sec	79.65
2	Constant Spiral	33min 15sec	84.17
3	Parallel Spiral	32min 59sec	82.75
4	Parallel Spiral, Clean Corners	34min 23sec	86.92
5	Morph Spiral	39min 38sec	100
6	One way	33min 14sec	84.15
7	True Spiral	37min 59sec	95.45

G. Contour toolpath optimization

TABLE VI.   EXPERIMENTAL MACHINING TIME FOR CONTOUR TOOLPATH (6MM TOOL DIA.)

Sr. No	Toolpath	Tool Dia. (mm)	Experimental Machining (min)
1	2D	6	31m 37sec
2	Ramp	6	26m 13sec
3	Remachining	6	31m 37sec

Contour 2D toolpath using of 6mm diameter cutting tool experimental machining time of 31m 37sec. Ramp toolpath experimental machining time of 26m 13sec is minimum.

TABLE VII.   EXPERIMENTAL MACHINING TIME FOR CONTOUR TOOLPATH (10MM TOOL DIA.)

Sr. No	Toolpath	Tool diameter (mm)	Experimental Machining (min)
1	2D	10	27m 35sec
2	Ramp	10	26m 13sec
3	Remachining	10	27m 35sec

Contour 2D toolpath using of 10mm diameter cutting tool experimental machining time of 27m 35sec. Ramp contour toolpath experimental machining time of 26m 13sec is minimum.

VII. RESULTS & DISCUSSION

Software simulation time, experimental machining time and difference of them are described in Table VIII. One way toolpath gives minimum time difference which is 0.32sec compare to other toolpath. Here Morph spiral toolpath gives maximum time difference between software and experimental machining which is 1m 13.27sec.

TABLE VIII.   COMPRESSION OF EXPERIMENTAL AND SOFTWARE MACHINING TIME

Sr. No	Toolpath	MasterCAM ® Software Simulation Time (min)	Experimental Machining Time (min)	Time Difference software & Machining
1	Zigzag	30m 45.62sec	31m 37sec	50.98sec
2	Constant Spiral	32m 33.44sec	33m 15sec	40.44sec
3	Parallel Spiral	32m 18.11sec	32m 59sec	41.89sec
4	Parallel Spiral, Clean Corners	33m 40.39sec	34m 23sec	42.61sec
5	Morph Spiral	38m 25.21sec	39m 38sec	1m 12.39sec
6	One Way	33m 13.28sec	33m 14sec	.32sec
7	True spiral	37m 26.40sec	37m 59sec	32.20

The simulation time and experimental time of One Way toolpath is almost same as the deviation is 0.32sec only.

A. Compression of simulated contour toolpath

Table IX describes software simulation, experimental machining time and their difference for various contour toolpaths having 6mm diameter. Ramp contour toolpath gives minimum time difference which is 43.13sec compare to other toolpath. Here contour 2D and Remachining toolpath gives maximum time difference between software and experimental machining which is 1m 50.98sec.

TABLE IX.   COMPRESSION OF SOFTWARE AND EXPERIMENTAL MACHINING TIME (6MM TOOL DIA.)

Sr No	Toolpath	Soft. Simulation Time (min)	Exp Machining time	Time Diff. soft.& Machine
1	2D	30m 45.62sec	31m 37sec	50.98sec
2	Ramp	29m 48.87sec	30m 32sec	43.13sec
3	Remachining	30m 45.62sec	31m 37sec	50.98sec

Table X describes software simulation, experimental machining time and their difference for various contour toolpaths having 10mm tool diameter. Contour 2D and Remachining toolpath gives minimum time difference of

37.95sec and Ramp contour toolpath gives minimum time difference of 40.13sec.

TABLE X.   COMPRESSION OF SOFTWARE AND EXPERIMENTAL MACHINING TIME (10MM DIA.)

Sr No	Toolpath	Soft. Simulation Time (min)	Exp Machining time	Time Diff. soft.& Machine
1	2D	26m 57.05sec	27m 35sec	37.95sec
2	Ramp	25m 32.87sec	26m 13sec	40.13sec
3	Remachining	30m 45.62sec	27m 35sec	37.95sec

VIII. CONCLUSION

The comparison of machining and simulation results shows that the best tool path depends on the geometry and the cutting conditions. The cutting tool takes non-productive time or "airtime" and need to be reduced. Amongst various cutting strategies available in MasterCAM® zigzag toolpath is found to be more favourable than any other strategies for rough machining of turbine blade involving minimum cycle time. Ramp contour toolpath for 6mm and 10mm tool diameter provides minimum experimental and simulated machine time. Ramp contour toolpath are more favourable than any other toolpaths. For the studied case, deviation of MasterCAM® software simulation time with experimental machining time may be due to time required for tool change in the CNC machine.

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