ADDING VALUE IN DESIGN-TO-MANUFACTURING PROCESS

Prasad V Rayasam
GE Aviation, Bangalore, India

Kapil Punja
GE Aviation, Bangalore, India

Mukund Tibrewal
Indian Institute of Technology, Delhi, India

Andrew King
GE Power, Bangor, USA

Peter Taft
GE Power, Bangor, USA

Vikas Singh
GE Aviation, Bangalore, India

Abstract

This paper discusses how design for manufacturability can result in creating a lower cost product to meet all performance targets. Integration and collaboration between design and manufacturing teams result in questioning legacy product features and developing new ones that meet performance & manufacturing criteria. In this paper we discuss one specific example of design for manufacturing of airfoils for modern day Turbines. Generation of 5-axis CAM toolpath for airfoil machining is a complex process. There is high value in designing "manufacturable" or producible airfoil CAD models at the design phase to ensure reduced rework to fix geometry inconsistencies during the manufacturing phase. We discuss common issues faced during machining of airfoils and how they can be mitigated with better airfoil design in conceptual design phase. Though authors did not explicitly follow SAVE recommended value engineering steps during the execution of this project, in hindsight, the mindset required and employed by entire global team was no different than the spirit of value engineering.

The main challenge faced in creating such mindset is many times lack of awareness and in-depth knowledge of design requirements by manufacturing engineers and lack of manufacturing constraints and cost functions by design engineers. One of the important enablers for breaking these barriers between design and manufacturing is CAD-CAM framework. What we learnt is the need for same set of tools or seamless integration of tools that is transparent to users in both communities and also need for "real time" feedback during design of features. An analysis was carried out of common problems faced during airfoil machining which are attributable to geometric inconsistencies. Algorithms were built to identify these geometry inconsistencies. These algorithms were used by preliminary airfoil designers to fix the identified problems in design phase. A steam turbine blade that was manufactured at GE Power business is used for this study. The results helped identify the airfoil geometric inconsistencies upfront and avoidance of re-work and failed toolpath creation during airfoil machining in the shop, resulting in several thousand dollars of benefit. Equally importantly, the process followed especially building an inter-disciplinary global team of design engineers and supply chain engineers/machinists has proven to be a best practice that is being replicated for other projects.

Introduction

In any manufacturing business, gaps in communication and lack of understanding across departments lead to increase in cost of all operations. Airfoil surface machining can become a time consuming and a costly process with inaccurate geometry properties or operation parameters. In this paper, we focus on few processes that are applied to make a specific airfoil part family by Manufacturing Engineering team at GE Power business. During root-cause analysis of machining process, curvature variation and spacing of inflection points played major role that directly influenced surface quality. Moreover, with increase in complexity of airfoil surfaces, optimal tool orientation control on a typical 5-axis milling machine becomes a challenge because of multiple kinematic solutions available on the machine.

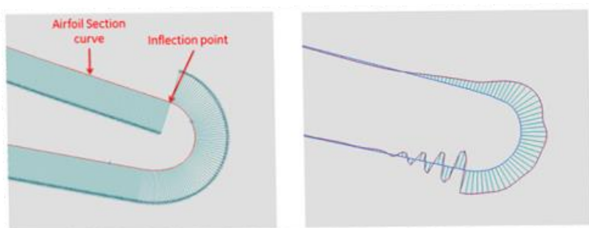

Fig-1 Comparison of possible curvature variation between different airfoils

It is observed that there is a considerable amount of time spent before and after airfoil machining, if a CAD model from the Design Engineering team comes with geometry irregularities. This leads to unnecessary cost that could easily be avoided if we can identify and fix (wherever possible) these geometry issues at the design phase. Without proper checks on such issues, manufacturing shops had to deal with either “fixing” the tool paths or “blending” machined parts on such airfoil designs. Hence, we have focused our efforts to check vane curvature quality and optimize the inputs to CAM software that considers curvature variation to generate a machining toolpath. For example, in Fig-1, output from a CAM toolpath can significantly vary based on the curvature variation.

Effect of CAM input parameters on toolpath output is validated using commercial software from Siemens NX™, customizable NX™ open source and using one of the basic toolpath strategies, Principal Axis Method (PAM) [1]. PAM strategy determines principle curvatures at cutter contact point and orients the minimum curvature of the tool with maximum curvature of the surface. There is also a need to understand recent trends in machining strategies that can result in minimum machining time (maximum material removal rate) while generating gouge-free surface within desired engineering tolerances [2]. More strategies such as Multi point methods (MPM) [3], Rolling Ball Method (RBM) [4], etc. were also published that showcased improved machining time. With these newer strategies, researchers are consistently bringing out novel methods to increase cutter contact area and thus reducing the time to machine a surface. We used Siemens NX™ software to understand the science behind these strategies by analyzing airfoil curvature dependency on the quality of machined surface.

Finally we developed few software tools so that user can analyze vane curvature quality and speed up programming time. The same software tools are also supplied to the Design engineering team, so that with prior checking, rework at downstream side can be avoided.

5-axis Toolpath machining: Effect of curvature

Typical advantages with 5-axis machining of any sculptured surface include cutting tool accessibility at different orientations, high material removal rate, and better surface finish. Optimal tool orientation needs to be programmed in order to achieve the above benefits. And the tool axis orientation is determined so as to avoid curvature gouge between tool and workpiece [5]. Even though Siemens NX™ CAM software provides optimal tool axis orientation and gouge correction, high manual user interaction is observed. With irregular curvature variation, CAM software creates unpredictable toolpath that needs to be verified by the user manually to avoid gouging, collision, scallops [Fig-2] that are detrimental to surface quality. ***Gouging*** refers to excess material removal due to cutting tool and part curvature mismatch. ***Collisions*** can happen either at the cutting region because of accidental rubbing of tool holder against the part surface or between two different machine components. ***Scallops*** [Fig-2] are caused due to improper path interval specification and result in poor surface quality.

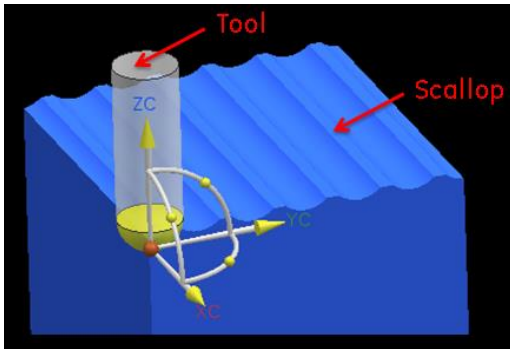

Fig-2: Scallops on work surface resulting in poor finish

Surface curvature plays an important role in tool axis orientation (lead and tilt angles) and cutting tool selection to avoid gouging [6]. ***Lead Angle*** refers to angle between tool axis and curvature normal (surface normal) defined in the direction of feed [Fig-3]. Optimum Lead angle is derived by matching curvature of tool and work surface so as to avoid gouging. ***Tilt Angle*** refers to angle between tool axis and curvature normal in direction perpendicular to feed.

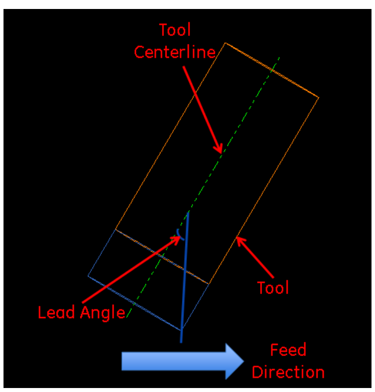

Fig-3: Lead Angle between tool axis and surface normal

Inflection point refers to a point on the curve where the surface changes from convex to concave shape, or where a change in curvature direction is observed. For example, there is only one inflection point that is marked in Fig-1. Identifying the inflection point's accurate location and the number of inflection points on each section curve of the airfoil are the major considerations for improving the tool path. In an airfoil section, there will be a minimum of two inflection points, one at the leading edge and one at the trailing edge. However, based on the profile of the airfoil, there could be more.

Adding Value within Design to manufacturing process flow

In a typical design to manufacturing process flow diagram shown below [Fig-4], there will be always a value-added benefit with manufacturability checks or optimal CAM programming. We introduced easy-to-use software tools to aid a CAM programmer that avoids cost of producing undesired parts with poor surface quality.

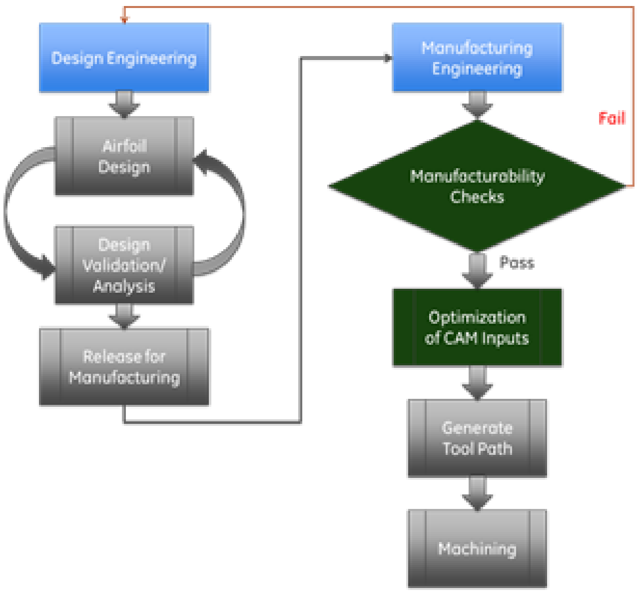

Fig-4 Typical Design-to-Manufacturing process flow with Manufacturability checks

Manufacturability Check: Vane curvature quality

To add value in the process of Design-to-Manufacturing, a software application is built that checks the quality of vane curvature on the CAD models released by the Design Engineering Team. This application enables the manufacturing engineer to analyze curvature variation across inflection points on any section curve. If the curvature variation is within the threshold limit, the application "passes" the airfoil. In certain designs where the curvature variation is beyond the threshold limit, the manufacturing engineer reaches out to the Design Engineering team with the concern. This simple process of having a validation application realized nearly 20 thousand dollars annually per vane family to the business.

Improve programming time: Optimal CAM inputs

5-axis toolpaths are generated with NX™ CAM application and efforts are put to evaluate options available for a standard CAM programmer. During this evaluation, it is observed that a CAM programmer spends time to define additional support geometry required to create toolpaths. Also, default values are input into some CAM software dialogs based on previous experience instead of geometry-based inputs. When there are any geometry issues, unnecessary time is put on debugging to find the root cause and occasionally correction could be applied to a wrong dialog. A steam turbine blade is used that is currently manufactured on a 5-axis dual rotary table milling machine. CAM toolpaths are defined starting from roughing the billet till finishing the airfoil shape.

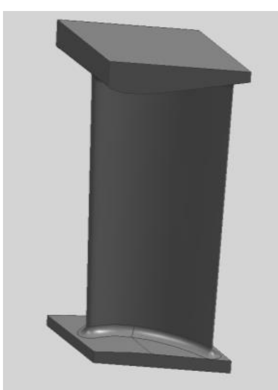

Fig-5 Steam turbine blade (representation only)

Lead angle prediction:

One of the continuous 5-axis CAM operations that machine mid airfoil section is used to validate the lead angle calculation theory based on PAM [1]. A software application that reads in airfoil surface and cutting tool (bull-nose) parameters is developed so that the user can start with geometry dependent lead angle calculation instead of trial and error. At this time, surface gouge checks are not built into the calculation. Instead NX™ in-built software capabilities are used to verify gouge-free toolpath and allowing NX™ to fine-tune the input lead/tilt angles. One of the major advantages with this tool is that the programmer will spend less time in trial and error and would not make any unwarranted changes to lead angle values if there are any issues during toolpath generation.

Surface split tool:

Due to high curvature variation around trailing edges, it is observed that divided surfaces instead of a single surface as drive geometry would avoid large rotary moves around such regions. A software tool is developed so that user can split the geometry automatically with minimal input.

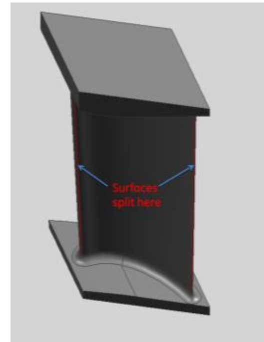

Fig-6 Split surfaces at LE and TE (representation only)

Curve smoothening tool:

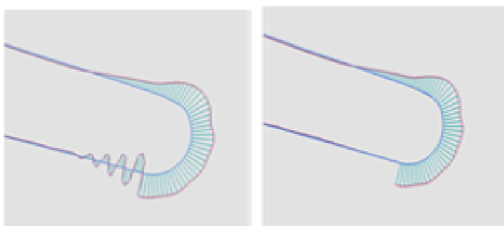

Fig-7 Curvature plots using smoothening tool

With the Vane curvature quality check tool, fail/pass criterial for a design is established. While Design engineering team reviews their process, an alternate solution was proposed to allow CAM programmer to alter the spline geometry. For this particular case study, automated software tool has shown deviation between old and new curves within the range of 0.4 – 0.6 mil. Usage of this particular tool is against the design philosophy as this can cause problems during CMM inspection checks, where original geometry is used. Nevertheless it identified issues with the geometry and allowed programmer to “not” apply corrections inside CAM inputs.

Discussion

The authors would like to acknowledge the very interdisciplinary and boundary-less working between team members and stakeholders to make this project successful. Just like emphasized in Value Engineering principles, the team brainstormed early in the project and identified major rework issues at manufacturing shop. After this, design engineers worked with manufacturing to understand why the issues were occurring and what the alternative geometry specifications that would reduce scrap are. Based on a continuous dialogue, design engineers were able to appreciate ground realities in the shop floor and manufacturing engineers also understood the design intent of these difficult to make features. With continuous engagement of manufacturing automation tools team, all stakeholders were able to identify what feedback design engineers need at design stage to help reduce manufacturing costs. After 1 year of tools deployment, this has now become a second nature and all the stakeholders – even though at different geographical sites- connect on new product/part and are able to use tools with minor tweaks to achieve improved FTY. The primary lesson learnt through execution of this project is – in today’s world – manufacturing is everybody’s business and so is design. Add to this, the constant improvement in algorithms and reduction in computing time and one can have very real time manufacturing tools.

Conclusion

Working in a huge organization such as ours, cross functional teams usually face challenges working completely in sync with each other. On the flip side, it also provides huge opportunities to work on simple solutions to bring in value to the work we do. Manufacturing teams are the final recipients of all the work that the organization's engineering teams work on. They usually work on extremely tight schedules, with multiple suppliers to ensure a quality end product that meet all performance specifications. Therefore, empowering the manufacturing teams with research and technology that help them achieve their goals and simplifies their work is a great example of Value Engineering. While we focused on a specific Airfoils manufacturing process, we think the opportunities are limitless if we can leverage the lessons learnt and apply to other manufacturing shops. One of these software tools developed (Curvature Analysis) is already adapted by Design Engineering team to validate the model release process, further adding value. Based on the research study done using the rest of the software tools, NX™ CAM programming time is further reduced. With computer aided design, manufacturing and the associated software evolving at a fast pace, there is limitless scope to keep adding value in legacy processes, saving time, simplifying systems and achieving performance targets.

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