Process Visualization – the Sequel to NC Verification

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Abstract

Several physics-based process planning and optimization systems, based on tool force computations and termed process visualization, are emerging. The factors that influence the reliability of these systems in computing tool forces are summarized. While mathematically precise models are used by these systems for tool force prediction, real world considerations impact on the accuracy of the predictions. Most notably, tool wear – for which there are no general reliable predictive models outside of highly controlled laboratory conditions – can have a dramatic effect on the tool forces, even as the tool remains in an acceptable cutting condition. Effective physics-based process visualization must provide practical assistance to the machinist in setting process conditions (feeds, speeds, step over, depth of cut) that meet constraints related to CNC performance limits (spindle power and torque), part quality (surface accuracy and surface roughness) and tool health (chip thickness and tool stress). Recently real time, on-line systems have been developed that transparently capture and calibrate the significant model parameters that determine tool forces. These parameters are tuned to the particular tool and material being cut, providing a much more accurate procedure for tool force computation while additionally providing a useful measure of tool wear.

Keywords:
Smart machining, machining models, optimization, process visualization

1 INTRODUCTION

NC verification – geometry-based validation of the in-process and final part geometry based on a defined set of tooling, stock and tool paths – has become widely used, embedded in most CAM systems. NC verification is the technology of choice in detecting – before the part is actually machined – critical events such as the tool crashing into the part while still in rapid mode, cutting into a fixture as well as alerting the programmer/operator to an incorrect cutter compensation value that will lead to under or over-cutting the desired surface.

But NC verification provides an ideal part representation and, at least as currently codified, does not include such effects as tool and part deflection, surface location error due to tool dynamics, overshooting programmed tool coordinates due to acceleration limits, offsetting of the nominal tool tip position due to tool wear and CNC performance errors. While the NC verification model may report part and feature coordinates to high precision, in reality the as-cut part geometry may differ from the ideal part geometry due to the above considerations.

Further a purely geometric analysis will not assist in chatter avoidance, prediction of surface finish, whether the selected tool path might lead to a broken or damaged tool and whether the tool loads will exceed the capabilities of the CNC motors and drives

Process parameters such as feed rates and spindle speeds are still primarily set in CAM systems using a look-up table with the parameters often invariant for each tool while experiencing widely varying machining conditions. Selection of step over and depths of cut is often dependent on the skills and experience of the programmer. An intelligent process planning system would assist the programmer and operator in selecting cutting conditions, going well beyond the ideal geometry vailidation available with NC verification. Many of these process concerns depend on the details of the tool force as the material is being cut. Computation of these tool forces requires a suitable physics-based model.

A next generation smart machining system will integrate both geometric and non-geometric (tool force) considerations, assisting the programmer and operator in producing quality parts in modest production time avoiding, or at least predicting, tool wear and failure all within the capabilities of the selected CNC machining center. This integrated system will be referred to as “Process Visualization” in contrast to the geometry visualization available through NC verification.

2 CURRENT PROCESS PLANNING METHODS

In general, CAM systems do not directly consider tool forces. The programmer works from look-up tables in selecting feeds, speeds, step-over and depths of cut. A skilled machinist often uses these tables only as a guideline and selects the cutting conditions based on their experience. Unfortunately, such skills are in short supply and even a skilled machinist is still only making an educated guess as to the best cutting conditions when dealing with a new part.

Geometry-only feed rate optimization systems are available. In contrast to most CAM programs that set a single feed for each tool, these systems supply a unique feed for each tool move (even breaking tool moves into shorter moves in order to smooth out changes in feed values). Some are integrated with CAM systems and some are offered on a stand-alone basis. These geometry-based systems are particularly helpful in speeding up the cutting process when the tool is “cutting air.” Unfortunately, there are two limitations of geometry-only systems. First, the user must select some geometry-specific parameters such as chip load, material removal rate and cutter engagement angle. While helpful tables are available for selecting chip load, there are no good guidelines to assist the user in selecting the latter two geometric parameters. Secondly, these geometric quantities are one step removed from the physical object that is to be controlled – the tool forces. A geometry-only optimization system simply can not take into account all of the myriad physical influences on tool forces which, in turn, have a controlling effect on part quality, tool health and CNC performance requirements.

3 PHYSICS-BASED PROCESS VISUALIZATION

Tool forces depend on the tool path (tool and part geometry) and on the rate at which that path is traversed (feeds and speeds). Tool forces also depend on the material properties of the stock and the detailed geometry (rake, relief and helix angles) of the tool as well as tool preparation (honing) and coating. Tool forces increase dramatically with tool wear and these increased forces can cause damage to the flute or insert and/or total tool failure. Tool forces can also be influenced by external factors such as dry vs. wet cutting or even the quality of the coolant. A well crafted process visualization system must account, in some manner, for all of these influences on tool forces.

In addition to our own work in collaboration with the Univ. of New Hampshire [1-2], there are several emerging physics-based process modeling and visualization commercial systems [3-7]. Each of these systems computes tool forces derived from a physics-based process model. This tool force information is then used, in one manner or another, to assist the user in selecting a best feed and/or speed for each cutting operation.

Two key questions are: [1] How reliable are the computed tool forces and [2] how effective is this information in assisting the programmer/operator in selecting cutting conditions?

4 PROCESS VISUALIZATION RELIABILITY

Our experience is that tool forces may be reliably expressed in terms of certain physical parameters (called “cutting energies” or “cutting force coefficients”) and geometric quantities as in the following expression for the force on each tooth:

$$F = Kc*a*h(theta) + Ke*a \qquad (1)$$

Here Kc and Ke are the cutting energies associated with shearing action and edge or frictional terms respectively, a is the contact edge length of the tool and h is the chip thickness when the tooth is at the spindle rotation angle theta. This general expression needs to be refined to accommodate tangential, radial and axial contributions to the total force as, for example, described by Altintas [8]. The geometric quantities (contact edge length, chip thickness) may be suitably extracted from a geometry-based NC verification model, albeit under the assumption of ideal cutting conditions.

The physical parameters (Kc, Ke) are the primary source of uncertainty in the force calculation. These parameters depend on a number of factors including stock material, tool/tooth geometry (rake, relief and helix angles), tool coatings, tool preparation (honing), state of tool wear and coolant. The dominant influence on the cutting energies comes from the stock material. The cutting energies may be measured under controlled experimental conditions [8] using suitable force sensor equipment. The results of these experiments may be combined with the part program-dependent tool tip geometry for each tool cut to predict tool forces.

To our knowledge, there is no compendium of cutting energies for every conceivable cutting condition (coolant, tool/tooth geometry, part material,…). Third Wave Systems [9] is embarking on a calculation of cutting energies for over 100 part materials using their finite element modeling (FEM) system. While their FEM model is mathematically precise and state of the art, in fact the theoretical results depend critically on the assumed constitutive model and may not conform with practice. Jerard [10] has found that even for nominally the same material and a similar tooling (but from a different manufacturer), cutting energies can vary by as much as 30%. There is experimental scatter even for identical part and tooling. A finite element model is unlikely to incorporate such effects on tool forces as coolant and can not account for local hard spots or other variance (e.g. heat treatment) in as-delivered materials nor variance in tool quality between manufacturers or even from the same manufacturer.

As with NC verification geometry modeling, the tool force modeling provided by extant physics-based process modelers is not a mathematically precise science. The results are certainly useful and provide valuable guidance, but should not be considered as an absolute standard. In most cases, 10 to 20% errors in force predictions can be expected, but the user must be prepared for even larger errors in any physics-based system that relies on pre-calculated tabular cutting energies.

All of the above assumes a sharp tool. In fact, a worn tool that is still acceptable in practice can experience tool forces (and, hence, cutting energies) that are two to three times (200-300%) larger than the sharp tool values [11]. The approaches to handling tool wear may be broken into two camps. One solution is to arbitrarily assign some factor to increase the tool forces as the tool is put into use. The term “arbitrary” is employed since, in fact, there is really no guidance on what factor to use.

A second solution is to assume some sort of Taylor-like relation between tool wear and the feeds, speeds and depths of cut [7]. These relations are extracted under highly controlled laboratory conditions with fixed axial and radial depths of cut for very particular tooling and part materials. The variance in the Taylor expression over a range of tooling and materials, let alone when cutting at variable depths of cut, remains a matter of laboratory investigation. In addition, to our knowledge, there is no general relationship between the tool life, as predicted by the Taylor expression, and the quantitative effect of the current state of tool wear on the tool forces.

In sum, current physics-based process visualization systems are valuable in providing general guidelines in computing tool forces. This information is greatly superior to the educated guesses made by even an experienced machinist. However, the user is cautioned not to consider the computed tool forces to have high precision.

5 PROCESS VISUALIZATION EFFECTIVENESS

Severa l of the process visualization systems, mentioned above, emphasize tool forces in reports to the user. But few machinists care or even understand what a tool force might be at any instant in time. Their concerns are the quality of the final product, the health of the tool during that process and whether the process will exceed the capability of the selected CNC machining center.

We suggest that, particularly in view of the uncertainties in the underlying tool forces, that user simplicity should be a controlling feature of a process visualization system. The input should be couched in machinist-friendly terms as opposed to asking for parameter values that may be unfamiliar or have unknown values to the machinist. The output should similarly report items of interest to a machinist. In place of limits on tool forces, the machinist should be queried on what part tolerance (i.e. tool deflections) and what surface finish they require, what fraction of the expected tool breaking stress they will tolerate, what is the recommended chip load for this tool and material and what are the performance limits (motor power, maximum speeds and feeds) for their CNC machining center. By removing the user from concerns over detailed tool forces, such a system places the machinist back on familiar ground and in control of the process.

Process visualization systems excel at identifying sections of the part program where tool forces (or a process variable such as part tolerance, tool breaking stress, motor power requirements) approach extreme values. Some process visualization systems currently only optimize one variable at a time. There is the potential that when a second variable is selected, the first variable exceeds the preferred limit. A well-designed process visualization system will allow the user to identify limits on multiple process variables and simultaneously optimize/select suitable cutting conditions.

Process visualization systems assist the user in better understanding the critical sections of their part program and assist them in improving that part program. Emphasis is on the physical aspects of program concerns, incorporating geometric validation through NC verification. While the reports and recommendations necessarily lack mathematical precision due to real world variations in tooling, materials and cutting conditions, they are still far preferable to an educated guess.

6 NEXT STEPS

To date, all process visualization systems are software-based. That is, the critical parameters (the cutting energies) are all based on tabular values. Since the cutting energies may vary even for nominally the same material and tooling, this leads to a loss in accuracy in the tool force computations.

Xu [11] describes an integrated hardware-software approach that determines the cutting energies *in situ* from monitoring the spindle power. This will greatly reduce the uncertainty in the cutting energies and cutting forces. Most importantly, the variation in the cutting energies and tool forces may be non-intrusively monitored as the tool wears. The merger of this hardware-software solution with a process visualization module will provide a more robust and much more accurate system that, for the first time, reliably and seamlessly incorporates the effects of tool wear.

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