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Correlation between machining direction, cutter geometry and step-over distance in 3-axis milling: Application to milling by zones

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ABSTRACT

Computer-Aided Manufacturing (CAM) occupies an increasingly important role in engineering with all it has to offer in terms of new possibilities and improving designer/manufacturer productivity. The present study addresses machining of free-form surfaces on a 3-axis NC machine tool. There have recently been a large number of studies devoted to planning tool paths on free-form surfaces with various strategies being adopted. These strategies are intended to increase efficiency by reducing the overall length of machining. Often, the choice of the cutter is arbitrary and the work focuses on planning. In order to boost productivity, the present work offers assistance in choosing the cutting tool, the machining direction and cutting by surface zones, adopting a milling strategy by parallel planes. To do so, a comparison is made between milling using a spherical end milling cutter and a torus end milling cutter with the same outer radius. This comparison relates to the radius of curvature of the trace left by the cutter at the point of contact between the tool and the workpiece in relation to the direction of feed motion.

1. Introduction

Free-form parts have become a regular feature of our daily lives. These harmonious shapes answer to criteria of style or are of a functional nature and require an ever higher level of quality. Moulds and dies are examples of parts that are mainly made up from free-form surfaces. They require good surface conditions and extremely reduced shape defects.

Machining moulds or dies is a long and costly process. Considering the time needed for finishing and polishing operations for free-form surfaces it can be seen that the latter can represent a considerable part of the overall machining time. One of the goals with automatic path generation is to obtain planning that will tend to minimise finishing and polishing operations over the entire surface while maintaining reasonable productivity.

Until now, methods for automatic generation of paths as currently used have included milling using guide surfaces [1], parallel plane milling [2] and iso-parametric milling [3]. Parallel plane milling has the advantage of generating paths that do not overlap, which limits the appearance of non-machined areas. But this strategy is not optimal in terms of cutter paths and scallop height. For example, if you mill a work-piece with considerable variations from the normal, you will see a contraction of the successive passes due to the need to respect the scallop height. The loss of time and thus of productivity arises from poor control over the scallop height along the paths: only the maximum scallop height produced is known [4]. This observation led to the notion of "generation of paths with constant scallop height".

A considerable number of works have been devoted to calculating the scallop height within the scope of free-form surfaces. Warkentin et al. [5] stated the problem for a spherical end milling cutter, [6] addressed the issue for a flat end milling cutter tilted by an angle in the direction of milling, and [7] concentrated on torus end milling cutters for 5-axis machining. These studies were conducted in an algebraic manner from simplified hypotheses: constant curvature, approximated cutter geometry and planar studies. Using such approximations within the framework of algebraic methods leads some authors to implement numerical methods for scallop height calculation [8]. For a spherical end milling cutter, various methods [9–12] have been studied to work from each point of a path and then compute the position of the points for the following path and so respect an imposed scallop height.

Another idea developed in the literature that also uses numerical resolution is that involving the "swept surface" [13]. The surface swept by the cutter is the surface of the volume removed by the cutter as it follows its path. Determining this surface can be an easy matter in some cases, but much more complex in others. For example, for a spherical end milling cutter, it will be extremely easy to determine the surface envelope as this will be the surface generated by a sphere whose radius is that of the cutter and

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whose centre moves on the path of the CL cutter location points. However, finding the surface envelope generated by a torus end milling cutter is a much more awkward problem. In [14,15], a calculation method is adopted to give an approximation of the surface swept by the cutter during 5-axis machining with a torus mill.

Several types of milling cutters are currently used in 3-axis milling: spherical end cutters, flat end or torus end cutters. The commonest choice is the spherical end cutter and a number of research works have been conducted into the choice of dimensions for such a tool. Thus, Lo [16] presents an extremely widely used method to address milling using a spherical end milling cutter: firstly a cutter whose diameter is as large as possible is used to remove as much material as possible. The cutter leaves un-machined areas behind it that correspond to zones of local interference. A tool whose diameter is defined in relation to the curvature of the un-machined zones is then used. The criterion of choice for the large diameter tool is based on minimisation of the "overall length of the paths covered by the two cutters". Lai et al. [17] propose a different approach suited to pocket machining and sizes the large cutter in relation to the minimum dimension of the pocket. Meanwhile, Vickers and Quan [6] addresses the comparison of flat end or spherical end milling cutters in relation to the effective radii of the tools. This study was only conducted for the case of milling a plane surface. In the studies concerned, the choice of cutter (often spherical) is only stated to eliminate collisions. In the article by Lasemi et al. [18], it is clearly stated that the choice of cutter in 3-axis machining of free-form surfaces is only calculated to avoid local interference between the tool and the surface. The cutter choice (geometry and size) for convex surfaces is never proposed as all types can be used. This is clearly a shortcoming as when you analyse the performance of CAM programs various strategies are implemented with no accompanying assistance in the choice of cutter. Taking a look, for example, at the possibilities for milling a surface in 3 axes on a Catia V5R19 or Topsolid, various strategies are on offer but the choice of cutter and the machining direction are left for the user to decide on.

Often the studies presented focus on a single tool geometry. Reducing machining time on a 3-axis machine involves diminishing the overall path to be covered while respecting a maximum scallop height. When the toolpath is made up of small, line segments, the milling time is not proportional to the distance covered [19], but a reduction of the overall length will allow for shorter machining time. To reduce the length of milling, the distance between the passes must be as big as possible to reduce their number. With this aim, a series of works was based on initial tool paths in the direction of the largest slope [20–23]. The authors show that such paths can quickly lead to looping between successive passes. To avoid this, they mill by zones, eliminating loops. Working from a first path, the following paths are calculated to respect the scallop height. The next paths gradually deviate and lose their orientation along the steepest slope. The machining strategy's validity becomes questionable as the step-over distance ceases to be optimal. The purpose of the present work is neither to seek to determine locally an optimum direction at a given point nor a maximum permissible scallop height but rather to contribute a global improved solution using an indicator λ. λ represents the ratio between the step-over distance of a torus cutter and the step-over distance of a spherical cutter.

The present article focuses on the choice of milling cutters and the machining directions to be favoured in 3-axis machining of a free-form surface using a strategy of parallel planes. The method for choosing the cutter is not based on local sizing for it to be outside interference in the concave areas of the workpiece. Where the cutter chosen cannot reach all the areas of the workpiece to be machined due to problems of interference, those left behind will then be reworked by smaller-sized cutters [24]. The method described allows the cutter geometry to be correlated with the milling directions by computing the radius of curvature for the trace left by the cutter at a point.

In order to generalise the study, a torus end milling cutter was chosen. A flat end mill or a spherical end milling cutter are just specific instances of the toroidal cutter.

The article is organised as follows: in Section 2, computation of the envelope curve of a cutter, computation of the effective radius and calculation of the step-over distance in relation to the cutter geometry and the surface and direction of milling are introduced. Section 3 is devoted to the study of parameters having an influence on the step-over distance. In this section, an essential relation is established in order to define the angular domain for which a torus milling cutter is more effective than a spherical cutter. The surface can be broken down into zones based on this angular domain combined with a representation of all directions of steepest slope of a surface. Applying appropriate milling directions to these zones allows machining times to be reduced considerably. Section 4 covers an application to validate the method and help in choosing the cutter. Having considered this example, the method's potential in studying machining strategies is demonstrated.

2. Envelope curve, effective radius and step-over distance

The present section proposes to compute the effective radius R_{eff} for each cutter geometry. The reasoning is pursued for a torus end milling cutter with torus radius r and cutter radius R. By extension, the effective radius R_{eff} of a flat end cutter will be determined taking $r = 0$ and that of a spherical end cutter taking $R = r$. Computation of the effective radius requires knowledge of the cutting tool envelope curve. The main stages in determining an envelope curve are recalled below.

2.1. Determining the swept curve

In this subsection, the principle of the swept curve for a torus end milling cutter on a 3-axis NC machine tool is introduced. Let $\mathbf{S}(u, v)$ be the surface to be machined. The global reference in which the surface is expressed (Fig. 1) is called $\Re_s(\mathbf{O}, \mathbf{x_s}, \mathbf{y_s}, \mathbf{z_s})$. The axis $\mathbf{z_s}$ of this reference is the machine spindle axis. Cutter positioning in the machine tool space is performed by programming the tool centre point denoted $\mathbf{C_L}$. For each point $\mathbf{C_C}$ of $\mathbf{S}(u, v)$, the cutter is positioned tangential to the surface $\mathbf{S}(u, v)$ through point $\mathbf{C_L}$ defined by:

$$\mathbf{OC_L} = \mathbf{OC_C} + r\mathbf{n_{CC}} + (R - r)\frac{\mathbf{z_s} \wedge (\mathbf{n_{CC}} \wedge \mathbf{z_s})}{\|\mathbf{z_s} \wedge (\mathbf{n_{CC}} \wedge \mathbf{z_s})\|} \quad (1)$$

with $\mathbf{n_{CC}}$ the normal to the surface at point $\mathbf{C_C}$.

Let $\Re_\alpha$ $(\mathbf{C_L}, \mathbf{x}_\alpha, \mathbf{y}_\alpha, \mathbf{z}_\alpha)$ be a reference such that the direction of feed motion $\mathbf{V}(\alpha)$ belongs to the plane $(\mathbf{x}_\alpha, \mathbf{z}_\alpha)$.

$\mathbf{V}(\alpha)$ in $\Re_\alpha$ is defined by:

$$\mathbf{V}(\alpha) = \begin{pmatrix} 1 \\ 0 \\ a(\alpha) \end{pmatrix}_{\Re_\alpha}. \quad (2)$$

$a(\alpha)$ is calculated for the cutter to move tangentially to the surface $\mathbf{S}(u, v)$ at the point. The tangent plane is defined by $\mathbf{n_{CC}}$; this translates by:

$$\mathbf{V}(\alpha) \cdot \mathbf{n_{CC}} = 0. \quad (3)$$

As the cutter moves, it will generate a surface called the "sweep surface". This is the surface envelope for the set of successive cutter positions. The sweep surface is thus the convergence of the set of profile generators for the cutter obtained for each position.