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Optimize tool paths of flank milling with generic cutters based on approximation using the tool envelope surface

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ABSTRACT

This paper presents a global optimization method to generate a tool path for flank milling free-form surfaces with a generic cutter based on approximation using the tool envelope surface. It is an extension of our previous work [Gong Hu, Cao Li-Xin, Liu Jian. Improved positioning of cylindrical cutter for flank milling ruled surfaces. Computer Aided Design 2005; 37:1205–13]. First, given initial tool path or tool axis trajectory surface, the grazing points of the tool envelope surface can be calculated. Second, the errors between the tool envelope surface and the designed surface along the normal direction of the tool envelope surface are calculated. Based on this new definition of error, an optimization model is established to get the global optimized tool axis trajectory surface. In order to simplify the calculation, two variants of this method based on the least square criterion are proposed to solve this model. Since this method is really based on the tool envelope surface, it can reduce the initial machining errors effectively. The proposed method can be used not only for cylindrical cutters and conical cutters, but also for generic cutters with a surface of revolution. In addition to ruled surfaces, it also can be used for machining non-ruled surfaces. Finally, several examples are given to prove its effectiveness and accuracy. The generated tool paths and calculated grazing points for test are available in supplementary files for the readers' convenience in verifying this work in different CAD/CAM systems.

1. Introduction

The 5-axis machine tool has been used widely in the manufacturing industry because it has great flexibility. Lots of papers focus on the optimization of tool paths based on all kinds of objectives, such as machining accuracy, avoiding interference [1] or reducing cutting force [2]. In this paper, we will focus on optimizing the tool path to improve the machining accuracy. At present, two methods are used in finish machining: point milling and flank milling [3]. Point milling uses the end of a cutter to cut the workpiece. Maybe it is more accurate to call it end milling. It suits all kinds of complex surface [4], but has low machining efficiency. In contrast, flank milling technology is to cut the workpiece using the side of a cutter. It has been proved an effective method for improving efficiency by increasing the machining strip width, especially for machining blades with ruled surfaces. In addition, compared with point milling, flank milling has a longer tool life and higher surface quality. But, it is very difficult to control finish machining errors due to the complexity of calculating the tool path. Therefore, many researchers focused on how to find precise and robust methods to calculate the tool path for flank milling.

Liu et al. [5] presented a double point offset (DPO) method for cylindrical cutters. He takes two points on a rule at parameter values of 0.25 and 0.75, then offsets a distance equals to the cutter radius along the normal vectors of the designed surface. The tool axis orientation can be defined by joining the two points. Tsay et al. [6] established an analytical model for a cylindrical cutter by considering the errors between the designed surface and the machined surface. Then the statistical analysis method is used to minimize the machining errors. Redonnet et al. [7] positioned a cylindrical cutter tangent to the ruled surface at three points. Tool positions are obtained by solving a system with seven transcendental equations. Bedi [8] let the cylindrical cutter slide along two directrices, keeping the cutter tangent to the two directrices. Based on Bedi's method Cornelia Menzel [9] presented a three-step optimization method to position the cylindrical cutter tangent to two parameter curves and a ruling. Monies [10] extended Redonnet's [7] method from cylindrical cutter to conical cutters. Chih-Hsing Chu et al. [11] use a developable surface to approximate an undevelopable ruled surface to eliminate local tool

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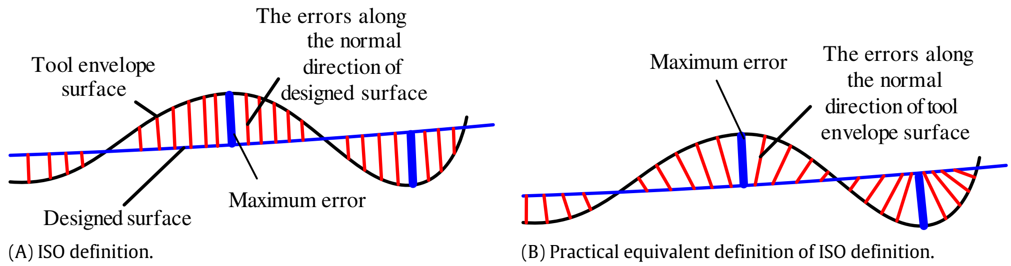

Fig. 1. Two definitions of errors.

interference in 5-axis flank milling. Sprott et al. [12] presented a method to generate the tool path with a cylindrical cutter based on a line geometric representation. Flank milling technology is also used in tool path generation of rough machining a centrifugal impeller [13].

As we all know, true machining errors are errors between the designed surface and the tool envelope surface. But the tool envelope surface is unknown before obtaining all tool positions. So it is difficult to optimize tool positions and consider the true errors at the same time. In most papers above, the authors tried to make some specific regulation to optimize tool positions and consider the relationship between the tool envelope surface and the designed surface less. In order to compensate for this deficiency, some methods are presented based on the tool envelope surface. Lartigue [14] gave a new idea to optimize tool positions based on the envelope surface by deforming the tool axis trajectory surface. But they use a "static instance of the tool" instead of the true errors, which is an estimation of the errors between the tool envelope surfaces and the designed surfaces. Another tool positioning method was presented by John CJ. Chiou [15]. First, initial tool positions are calculated. Second, the initial tool positions are corrected to make the overcut into the undercut. But the error range is not reduced. By considering the envelope surface, Senatore et al. [16] analyzed an improved positioning method for flank milling a ruled surface using a cylindrical cutter. Further, the rotation axis's influence on machining errors is analyzed [17]. Hu Gong et al. [18] presented an improved tool positioning method for flank milling a ruled surface based on the envelope surface. This method transforms one problem approaching the designed surface with a tool envelope surface into another problem approaching the offset surface of the designed surface with a ruled surface. A least squares model is established to get the optimized tool axis trajectory surface. This method is accurate, but only fit for cylindrical cutters. Senatore et al. and Ding et al. [19,20] also give different optimization methods using offset surface characteristics. Wu et al. [21] presented a tool path planning method for 5-axis flank milling using a cylindrical cutter based on dynamic programming.

According to the introduction above, we know that there is a great improvement on the flank milling technique, but some problems still restrict the application of this technique. These can be summarized as follows: (a) Cylindrical cutters have been studied widely. In contrast, there are fewer studies on conical cutters even no studies on generic cutters. Furthermore, for different cutters there are different methods, which make the application of flank milling technique in CAM system inconvenient. (b) Precision and robustness need further improvement. In order to solve these problems to some degree, a new tool positioning strategy for 5-axis flank milling is presented based on the envelope surface in this paper. It can be used for tool path optimization of flank milling free-form surfaces with generic cutters with a surface of revolution, such as cylindrical cutters, drum cutters, conical cutters, and so on.

2. Principle of global optimization of tool positioning for flank milling

2.1. Practical equivalent definition of ISO error

A tool positioning strategy has been proposed for cylindrical cutter flank milling ruled surfaces with the least squares method in our previous paper [18]. This method yields good results based on the tool envelope surface. But it greatly depends on a special characteristic of offset surfaces and is only fit for cylindrical cutters. In general, most other cutter surfaces do not have this special characteristics, such as a conical cutter or a drum cutter. Therefore, it is necessary to extend this work to non-cylindrical cutters.

As shown in Fig. 1, (A) shows the definition of error in the ISO standard, in which the error is the distance between the designed surface and the tool envelope surface along the normal direction of the designed surface. As we know, this definition of error is widely used to evaluate the machining precision in industry. But it is inconvenient to use it to optimize the tool path directly. In order to solve this problem, some researchers proposed different definitions of error to optimize the tool path [3,14,22,23]. Obviously, the definition of error is very important to the final optimized result because it is the key link between the tool axis, the tool envelope surface and the designed surface. In this section, we present a practical equivalent definition of the ISO error to optimize a tool path, as shown in Fig. 1(B). The error is the distance between the designed surface and the tool envelope surface along the normal direction of the tool envelope surface. Obviously, the local maximum errors of two definitions are equivalent because the two normal directions are same. It is easy to understand that: For smooth surfaces and small errors, if the error (B) decreases, the ISO error (A) must decrease too. Obviously, two definitions are equivalent for evaluating the machining precision. In the next section, a basic optimization model based on the definition of error (B) will be presented.

2.2. The basic idea of optimizing tool path

As shown in Fig. 2, a tool envelope surface is generated from initial tool positions. Selecting any one tool position, a corresponding grazing curve can be obtained. We may pick any point p_t on the grazing curve. $\boldsymbol{n}$ denotes the unit normal vector of the tool envelope surface at point p_t. Obviously, $\boldsymbol{n}$ also denotes the unit normal vector of the cutter surface at this position. The normal line through the point p_t intersects the designed surface at point p_d. The distance between p_t and p_d is ε_0, which represents the machining error in this paper. The normal line intersects the tool axis at point q. By moving point q with the distance ε_0 along $-\boldsymbol{n}$, we can get point q_a, which is called a *map point*. If we move the cutter surface and let point q approach the point q_a, p_t approaching point p_d accordingly. Analogously, at every point on the grazing curve we can get a map point. All map points will form a curve, which is called the *map curve*. Obviously, when the