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Positioning method of a cylindrical cutter for ruled surface machining based on minimizing one-sided Hausdorff distance

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Abstract Motivated by the definition of the machining errors induced by tool path planning methods, a mapping curve of the tool axis of a cylindrical cutter is constructed on the tool surface. The mapping curve is a typical one that can be used to express the closeness between the tool surface and the surface to be machined. A novel tool path planning method is proposed for flank or plunge milling ruled surfaces based on the minimization of the one-sided Hausdorff distance (HD) from the mapping curve to the surface to be machined. It is a nonlinear optimization problem in best uniform approximation (BUA) or Chebyshev sense. A mathematical programming model for computing the minimum one-sided HD is proposed. The linearization method of the programming model is provided and the final optimal solutions are obtained by simplex method. The effectiveness of the proposed BUA method is verified by two numerical examples and compared with the least squares (LS) and double point offset (DPO) methods. The variation in tool orientation induced by the optimization of the tool positions is also evaluated.

1. Introduction

The ruled surface is widely applied in the fields of aviation, aerospace, shipbuilding and chemical industry as a functional geometric feature of some key components, such as compressor, impeller, blade, ATC cam, etc. With the increase of the required machining accuracy and efficiency, the highly efficient and accurate machining technology for these kinds of components has attracted considerable research attention. At present, the usage of non-ball-end cutters to machine free-from surfaces is an important way to get these goals and most of the researches in this field occur in some professional companies, such as NREC, HITACHI, SULZER and STARRAG, etc. The Flamingo project[1] was proposed by EU to improve the machining accuracy and efficiency of the key components of turbo machinery using flank milling method.

In the past two decades, much attention has been devoted to optimizing the tool trajectory of five-axis milling non-developable ruled surfaces to minimize deviations between the machined surface and the designed surface. The initial

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positioning methods for the machining of a ruled surface are basically direct offset methods. Liu[2] presented a single point offset (SPO) method and a double point offset (DPO) method for machining sculptured surfaces with a cylindrical cutter. For a ruled surface milling using the DPO method, two points located at one quarter and three quarters of the length of a ruling are selected and offset a distance equals the tool radius along the corresponding surface normal vectors, respectively. The radius vector joining the two offset points is set as the tool axis. Rubio et al.[3] developed a named standard positioning method for the machining of a ruled surface with a cylindrical cutter. The axis of the cylindrical cutter is parallel and at a distance of the cutter radius from the ruling considered. The final position of the tool axis is determined to ensure that the interferences on each of the surface directrices are equal. Although this kind of approach is easy to implement, the tool path planning errors involved are always significant due to the restriction of the ruled line considered.

In order to keep the cylindrical cutter tangent to the two directrices of a ruled surface, Bedi et al.[4] developed a method for letting the cutter slide along the two directrices. This positioning method requires the numerical resolution of a system of four equations with four unknowns and guarantees the tangency of the cutter with the directrix curves. Since it only ensures the cutter tangents to both directrices, a larger overcut is inevitable for the machining of a ruled surface. Motivated by Bedi's work, Menzel et al.[5] got the optimum tool position by adjusting the cutter's attitude to give it three tangency points with the ruled surfaces at each tool position.

Redonnet et al.[6] positioned a cylindrical cutter tangent to a ruled surface at three points, including two points on two directrices and one point on a ruling. As a result, they developed a system of seven transcendental equations that must be solved simultaneously to obtain each tool position. Senatore et al.[7] analyzed the positioning errors of the method[6] by comparing the envelope surfaces with the ruled surface, and validated the tool positioning method by a complete example. Monies et al.[8] extended this method to conical cutters. These methods are accurate but complex in terms of their computation.

Based on the offset theory of surface, Tönshoff and Rackow[9] presented a positioning strategy for flank milling ruled surfaces with a cylindrical cutter. In their work, the desired surface is offset at a distance of the tool radius firstly. Then, a ruled surface is used to fit the offset surface. The optimized ruled surface is the final tool trajectory surface. Gong et al.[10] proved that the envelope surface of a cylindrical cutter was the offset surface of the tool axis trajectory surface, and that the deviation at the extremum point between the designed surface and the envelope surface of a cylindrical cutter was equal to that between the offset surface of designed surface and the tool axis trajectory surface. They proposed a three points offset (TPO) strategy to position the cylindrical cutter initially for ruled surface machining and established a least squares approximation scheme to make the tool axis trajectory surface fit the offset surface of the designed surface as much as possible.

Considering that the trace left by the milling cutter in the material is given by the tool envelope surface[11], some researchers have evaluated machining errors and generated tool paths based on the envelope surface. Chiou[12] proposed a tool positioning method for machining a ruled surface with a conical cutter by analyzing the machining errors between the swept profile and ruled surface. Lartigue et al.[13] evaluated and corrected tool paths using the envelope surface of the conical tool based on the kinematics approach. The deviations between the envelope surface and the designed surface decrease when a least squares method is adopted to deform the initial tool trajectory and make the envelope surface fit the designed surface as much as possible. As the envelope surface can only be defined once the individual tool position is known, one cannot generate the tool path on the nominal surface of the workpiece directly. So, these kinds of methods require a great deal of computation. Gong et al.[14] proposed a Basic Curvature Equation of Locally Tool Positioning (BCELTP) method to calculate a second-order approximation of the tool envelope surface at the corresponding cutter contact point based on only one tool position. By using this method, the user can adjust tool positions individually until the relative normal curvature between the envelope surface and the designed surface is minimized.

Ding and Zhu[15] proposed an approach to optimize the tool path globally for the five-axis flank milling of a ruled surface with a conical cutter. By using the distance function, the tool path optimizations for semi-finish and finish millings are formulated as two constrained optimization problems, and a sequential approximation algorithm along with a hierarchical algorithmic structure is developed for the optimization. Zhu et al.[16] extended this method to conical cutters. Ding et al.[17] formulated the tool path optimization problem of a cylindrical cutter for flank milling as a fitting problem of spatial straight line based on Chebyshev norm and solved it via interior-point algorithms. However, the initial points for this fitting problem were set to be the offset points of the point on one v-parameter curve, i.e., a ruled line, of the ruled surface. This debased the optimization results of the method. Based on representing the swept envelope of a generic rotary tool as a sphere-swept surface, Zhu et al.[18] extended their previous works[15,16] to develop a method that can optimize both the tool path and shape for five-axis flank milling.

Considering that the flank milling is highly prone to machining chatter, Ahmadi and Ismail[19] presented a dynamic model to simulate the chatter in the time domain. Their results showed the importance of including process damping in a simulation model. Aimed at reducing machining errors, Hsieh et al.[20] proposed a tool path planning algorithm by using advanced particle swarm optimization methods for the flank milling of ruled surfaces.

In addition, other positioning methods for five-axis flank milling have been generated, and interested readers can refer to recent review papers for more information[21,22]. Although many methods have been proposed for five-axis flank and plunge milling, many seemingly good techniques are rarely used in the industry[4]. The key point is that the accuracy, robustness, efficiency and simplicity are the essential elements for a positioning method to be accepted by its end users.

For the existing tool positioning methods, the individual tool positioning method is very promising due to its good robustness and simplicity. However, the accuracy and effectiveness of these kinds of methods are related to the selection of the approximating objects and optimization models and require further investigation. In this paper, a novel tool path planning method is proposed for flank or plunge milling ruled surfaces based on the minimization of the one-sided HD[23,24]