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Research on Three-Dimensional Simulation of the Internal Arc Gear Skiving

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Abstract

Aiming at the problems that the simulation accuracy which is reduced due to the simplification of the model, a three-dimensional simulation method based on solid modeling is being proposed. By analyzing the motion relationship and positional relationship between the caries knife and the workpiece, the coordinate system of the caries machining was established. With the MATLAB software, the cutting edge model and the blade sweeping surface model of the boring cutter are sequentially established. Boolean operation is performed on the blade swept surface formed by the tooth cutter teeth with time t and the workpiece tooth geometry as well as the undeformed three-dimensional chip geometry model and the instantaneous cogging geometry model are obtained at different times. Through the compare between gear end face simulation tooth profile and the theoretical inner arc tooth profile, we verified the accuracy and rationality of the proposed method.

Keywords: *gear skiving; undeformed three-dimensional chips; solid modeling*

1 Introduction

The application of robots in the food industry, such as in food packaging, sorting, palletizing, canning, automated lunches, and automated cutting (beef), is becoming increasingly widespread. RV reducers is the core components of robots in the food industry, which is known for their strong impact resistance, high torque, high positioning accuracy, low vibration, and high gear reduction ratio. Due to their specialized application conditions, these RV reducers require large specifications, high precision, and impose stringent requirements on the manufacturing processes of their core components.

Scudding technology was named as Skiving or Power Skiving in abroad, which is an emerging gear machining technology in the 21st century [1]. It is highly efficient and precise, particularly suitable for machining non-through internal helical gears and high-precision non-involute gears using dry cutting methods [2].

Scholars at home and abroad utilize professional CAD/CAM/CAE applications to achieve simulation processing of power skiving and extraction of three-dimensional undeformed chips. Antoniadis [1-3] and others utilize the three-dimensional finite element software Abaqus to establish robust power skiving models and conduct finite element cutting simulations of the power skiving process. The simulation models reveal the direction of chip flow, showing good correlation between simulated and actual chips generated during machining. However, the accuracy of gear tooth profiles is relatively low, indicating significant discrepancies compared to real power skiving processes. Liu Bing [4-5] and his colleagues established gear tool geometry models which is based on gear meshing principles and obtain preliminary simulation data using DEFORM-3D software. The simulation accuracy is noted to be relatively low and it belongs to the exploration stage of gear machining.Yang Tangjun [6-7] and others utilize Vericut simulation software for geometric simulation of pre-angle power skiving cutter cutting processes. This approach provides an intuitive view of the three-dimensional geometric shape of gear teeth slots after power skiving. Nevertheless, issues such as improper tool design contribute to significant undercuts and overcuts, resulting in considerable disparities

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between simulation results and real power skiving processes. Zhao Haiyang [8] and his collaborators used numerical control simulation technology to construct a virtual simulation power skiving machine model. They achieve geometric simulation of the power skiving process and validate the correctness of the machine-tool movement relationship through Boolean operations to obtain undeformed chip shapes. However, precise analysis of gear profile machining results is not conducted.

At Harbin University of Science and Technology, Li Zhenjia [9-12] and others developed a chip breakage prediction system using the VisualC++6.0 development platform and OpenGL graphics language. They successfully extract three-dimensional undeformed chips. However, the chips extracted exhibit significant differences compared to those obtained from actual machining processes. Dimitriou [13-14] and colleagues implemented a power skiving simulation system to extract undeformed chips. Nonetheless, there is obvious deviation between predicted dynamic power skiving cutting forces and real observations.

Based on the above cases, this paper proposed a three-dimensional simulation method based on solid modeling which not only generates instantaneous tooth slot geometries that closely resemble those from actual power skiving processes but also extracts three-dimensional undeformed chips that closely approximate real-world power skiving results. This approach gets a solid foundation for research into the cutting mechanisms of power skiving, contributing significantly to the advancement of this machining technique.

2 Simulation Part

2.1 Three-dimensional simulation process of gear skiving

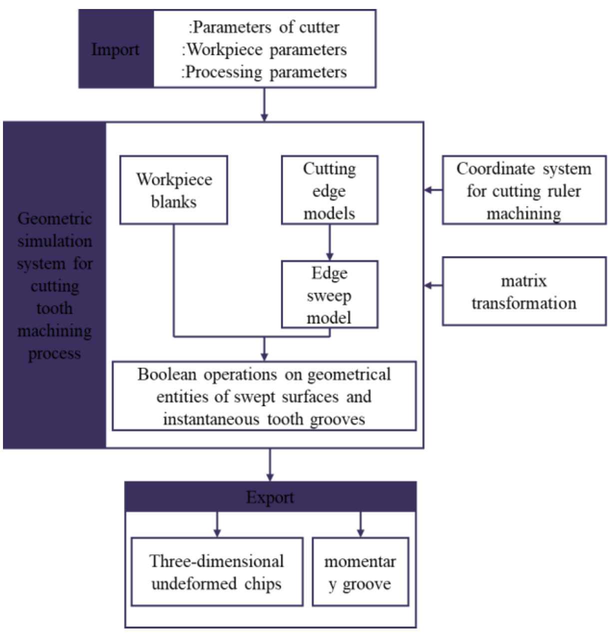


Figure 1 Three-dimensional simulation process of gear skiving

Figure 1 shows the three-dimensional simulation process of Gear Skiving based on solid modeling. After inputting the machining parameters, the simulation system automatically creates the geometric entity of the workpiece and constructs the cutting edge model. The cutting sweep surface model is determined based on the motion and positional relationships between the skiving and the workpiece. The workpiece blank is combined with the cutting sweep surface, and Boolean operations between the cutting sweep surface and the geometric entity of the instantaneous tooth slot form undeformed chips and new instantaneous tooth slots. After simulation completion, three-dimensional models of undeformed chips removed during the cutting process and instantaneous tooth slots are outputted.

2.2 Modeling of Ggear Skiving movement

Figure 2 shows the Gear Skiving coordinate system. Coordinate system $S_1(o_1, x_1, y_1, z_1)$ represents the workpiece coordinate system, while coordinate system $S_2(o_2, x_2, y_2, z_2)$ represents the tool coordinate system. $S_p(o_p, x_p, y_p, z_p)$ and $S_0(o, x, y, z)$ are auxiliary coordinate systems of $S_1(o_1, x_1, y_1, z_1)$ and $S_2(o_2, x_2, y_2, z_2)$, respectively. Coordinate system $S_1(o_1, x_1, y_1, z_1)$ is used to establish the workpiece tooth surface model, and coordinate system $S_2(o_2, x_2, y_2, z_2)$ is used to establish the tool model. Coordinate system S_p serves as an auxiliary system for S_1, and coordinate system S_0 serves as an auxiliary system for S_2, with fixed spatial positions for Sp and S_0. The center distance refers to the perpendicular distance between the tool axis and the workpiece axis, while the axis crossing angle refers to the angle between the tool axis and the workpiece axis. Table 1 presents the Gear Skiving process parameter table.

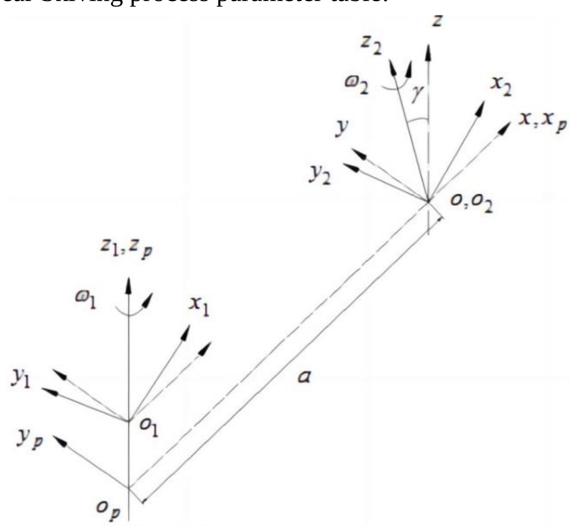


Figure 2 Gear Skiving coordinate system

According to the skivingbing coordinate system shown in Figure 2,the total transformation matrix from the tool coordinate system to the workpiece coordinate system is:

$$T_{20} = \begin{bmatrix} \cos\varphi_1 & -\sin\varphi_1 & 0 & 0 \\ \sin\varphi_1 & \cos\varphi_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$T_{op} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma & 0 \\ 0 & \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T_{p1} = \begin{bmatrix} \cos\varphi_2 & \sin\varphi_2 & 0 & 0 \\ -\sin\varphi_2 & \cos\varphi_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

In the formula, T_{20} denotes the transformation matrix from the tool coordinate system S_2 to the auxiliary coordinate system S_0, T_{op} denotes the transformation matrix from the auxiliary coordinate system S_0 to the auxiliary coordinate system S_p, and T_{p1} denotes the transformation matrix from the auxiliary coordinate system Sp to the workpiece coordinate system S_1.

The theoretical tooth surface of the cutting edge conforms to a conjugate relationship with the workpiece. The intersection obtained by intersecting a plane with the conjugate surface yields the cutting edge. By utilizing numerical discretization method combined with the process parameters in Table 1, the cutting edge of the skiving can be obtained. The three-dimensional simulation result of the cutting edge using MATLAB software is shown in Figure 3.

Based on the motion and positional relationships between the skiving and the workpiece, the cutting sweep surface model can be obtained. The three-dimensional simulation result of the cutting sweep surface using MATLAB software is shown in Figure 4.

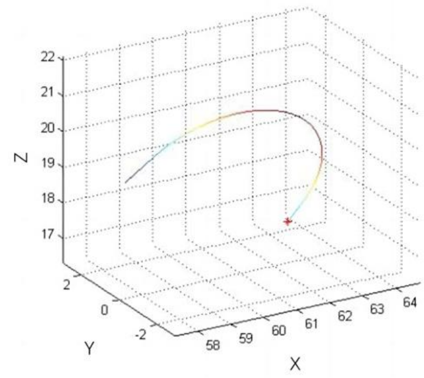


Figure 3 Simulation result of the cutting edge in MATLAB

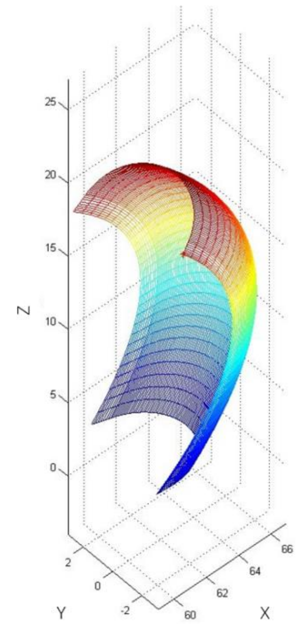


Figure 4 Three-dimensional simulation result of the cutting sweep surface

Table 1 Gear Skiving Process Parameters

Parameter type	Parameter Descriptions	Parameter Value
Cutting knife parameters	Knife teeth	22
	Knife helix angle	20 °
	Knife arc radius	5.8
	Knife pitch diameter	128
	γ_o Knife cutting front edge angle γ_o	5 °
	α_d Knife designing back angle α_d	6 °
Workpiece parameters	Teeth of workpiece	40
	helix angle of workpiece	0
	teeth width of workpiece	60
Machining parameter	Center distance	26.4525
	Axis crossing angle	20 °
	(mm/r)Axial feed rate/(mm/r)	0.15
	(r/min)Knife rotation speed/(r/min)	700
	(r/min) Workpiece rotation speed/(r/min)	385

2.3 Implementation of three-dimensional simulation process for Gear Skiving movement

In Gear Skiving, the radial direction is divided into multiple cutting layers for machining. The final accuracy of the tooth surface is ensured by the cutting process corresponding to the last radial feed. Therefore, this paper selects a cutting depth of 0.03mm for the final pass to discuss the machining process.

The three-dimensional simulation of Gear Skiving movement primarily involves removing workpiece material by Boolean operations between adjacent cutting sweep surfaces formed by successive skiving teeth over time t and the instantaneous tooth slots. The material removed from the workpiece constitutes the undeformed three-dimensional chips.

During Gear Skiving, the cutting sweep surface formed by a single skiving tooth over time t can only machine a portion of the tooth surface on the workpiece. To complete the entire tooth width, an axial feed motion is required. After a single skiving tooth completes a cutting pass with its cutting sweep surface over time t, upon the workpiece rotating one full revolution, another skiving tooth forms a cutting sweep surface over time t to continue machining the same workpiece tooth slot.

As shown in Figure 5, the subsequently formed cutting sweep surface translates forward along the tooth direction of the workpiece under axial movement. The material at the intersection between this cutting sweep surface and the previously machined tooth surface is removed, gradually shaping the machined tooth surface closer to its theoretical shape. This cyclic process repeats multiple times with cutting sweep surfaces formed by successive skiving teeth over time t, collectively completing the machining of the workpiece tooth surface.

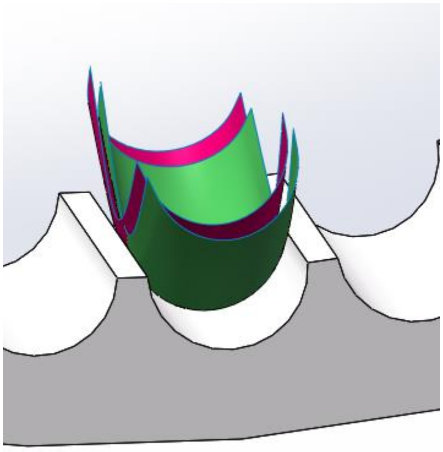
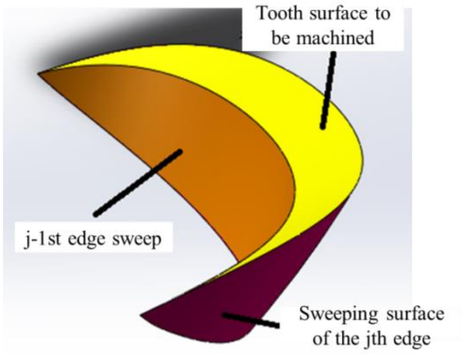
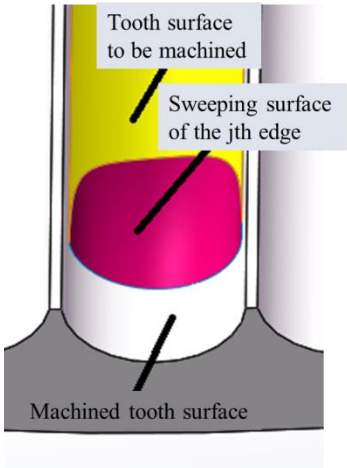


Figure 5 Schematic of the tooth surface formation process in Gear Skiving

Taking the j cutting sweep surface as an example, the undeformed three-dimensional chip is obtained by performing Boolean operations (difference and intersection) between the j-i cutting sweep surface and the j cutting sweep surface with the instantaneous tooth slot. Thus, the undeformed three-dimensional chip obtained after the j cutting sweep surface and its corresponding instantaneous tooth slot are shown in Figure 6.



(a) Undeformed three-dimensional chips



(b) Instantaneous tooth groove

Figure 6 Boolean operations between adjacent cutting sweep surfaces and the workpiece

3 Mulation Example and Result Analysis

The skivingbing tool employs an internal circular arc skiving, using internal spur gears as an example. Parameters are selected based on Table 1.

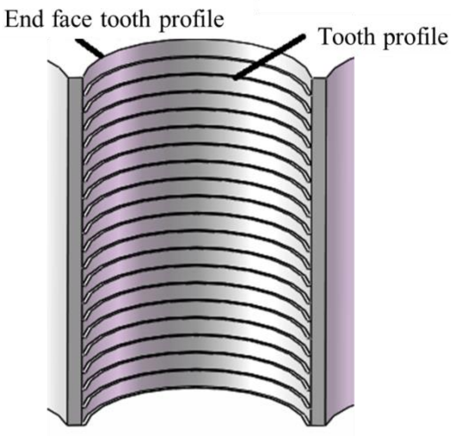


Figure 7 Simulated gear profile

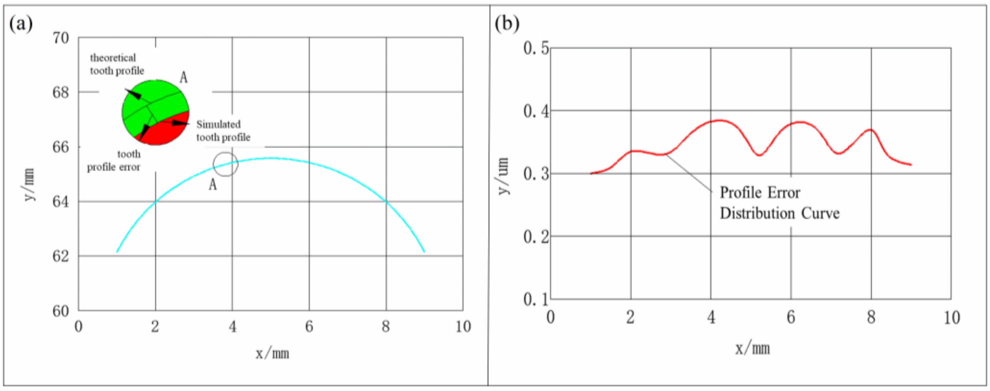


Figure 8 Simulated gear profile and its error:(a) Simulated gear profile and theoretical gear profile;(b) Gear profile error distribution curve

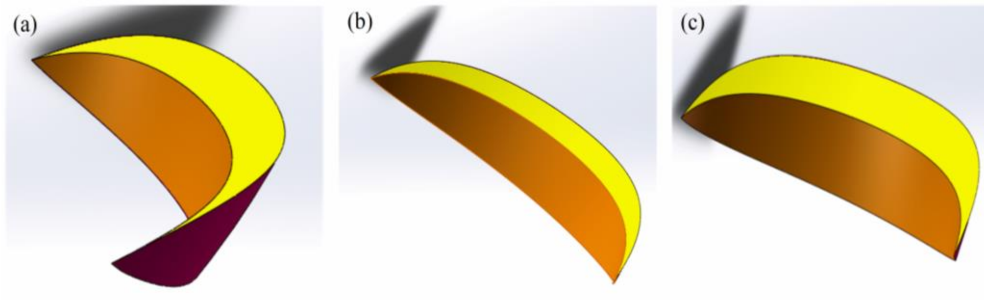


Figure 9 Three-dimensional undeformed chips at different time instants

Figure 7 shows the profile of the internal spur gear formed after simulation processing. Data points of the gear tooth profile extracted in the SolidWorks secondary development environment were subjected to curve fitting in MATLAB software. Figure 8(a) presents a schematic comparison between the simulated gear profile curve after fitting and the theoretical involute gear profile curve. The profile error distribution curve is depicted in Figure 8(b), showing the truncation error distribution of a skiving tooth without introducing artificial measurement errors. The error values are controlled within the range of 0.3μ~0.4μ, indicating the accuracy and rationality of the simulation method adopted in this study. Figure 9 illustrates the three-dimensional time t undeformed chips formed by the cutting sweep surfaces of different skiving teeth at various time instants.

4 Conclusion

Aiming the issue of reduced simulation accuracy due to model simplification, this paper proposes a three-dimensional simulation method based on solid modeling. The method involves performing Boolean operations between the cutting sweep surface formed by the skiving tooth over time t and the instantaneous tooth slot, thereby obtaining the geometric models of the instantaneous tooth slot and the undeformed three-dimensional chip. The comparison between the simulated gear's end face profile and the theoretical involute gear profile yields an error range of .3μ～.4μ, indicating reasonable accuracy of the proposed method.

The gear profile formed by simulation, after surface modeling, generates a three-dimensional geometric model of the gear that is useful for analyzing gear contact characteristics. The undeformed three-dimensional chips formed by simulation will provide a foundation for studying the dynamic cutting forces of skivingbing, as well as the cutting mechanics such as skiving wear.

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