ISSN: 2424-8460(O)
2251-2608(P)

Original Research Article

Tool path planning for NC machining of complex parts based on UG

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Abstract: With the ever-increasing demands for machining accuracy and efficiency of complex parts in the high-end manufacturing industry, tool path planning has become a key link in numerical control (NC) machining, which directly affects the machining quality and production cost of parts. To improve the machining efficiency and surface quality of parts such as complex curved surfaces and thin-walled structures, this paper discusses the application of UG software in tool path planning. First, by utilizing the parametric modeling and machining modules of UG, a multi-strategy collaborative path generation scheme including contour layered machining, adaptive region segmentation and spiral cutting was designed for complex geometric features. Second, the genetic algorithm was integrated to optimize the tool path, so as to reduce non-cutting travel and abrupt steering. Finally, the feasibility and safety of the planned path were dynamically verified through the cutting simulation and collision detection functions of UG. By means of UG and knowledge fusion tools, intelligent algorithms are deeply integrated with the Computer-Aided Manufacturing (CAM) process, realizing the collaborative and autonomous optimization of tool paths and cutting parameters.
Keywords: complex parts; UG software; NC machining; path planning

1. Introduction

With the transformation of the manufacturing industry towards high precision and high efficiency, the NC machining technology of complex parts has become the core competitiveness of modern industry[1] . Such parts are typically characterized by complex structures, variable curved surfaces and high precision requirements, and their machining quality and efficiency directly affect the performance and cost of the final products. In the NC machining process, tool path planning plays a crucial role. It determines the motion trajectory of the cutting tool, material removal efficiency, as well as the cutting force, vibration and thermal deformation states during machining, and is a key link to improve machining efficiency, ensure part surface quality and extend tool life . Scientific and reasonable path planning can reduce non-cutting travel time, optimize cutting load distribution, avoid interference and collision, and ultimately achieve high efficiency and stability in the machining process.

2. Application of UG software in NC machining

2.1. Functions and advantages of UG software

As an integrated Computer-Aided Design/Computer-Aided Manufacturing/Computer-Aided Engineering (CAD/CAM/CAE) solution, the core functional modules of UG software provide a solid theoretical foundation and practical platform for the NC machining of complex parts. Based on advanced parametric design and direct modeling technologies, the modeling module can efficiently construct 3D solid models with complex free-form surfaces and precise geometric relationships . The simulation module deeply integrates physical engines and manufacturing knowledge bases, which can simulate the material removal process and predict cutting force and thermal deformation in a virtual environment, providing a theoretical basis for path safety verification. The machining module integrates a rich strategy library and algorithm engine, serving as the core carrier for realizing automated and intelligent path planning, with the advantage of high adaptability in processing complex structures [2].

In the field of NC machining of complex parts, the unique advantages of UG software are reflected in the high efficiency and flexibility of path planning. High efficiency stems from its highly optimized algorithm core and parallel computing capability, which can quickly generate continuous tool paths covering complex cavities and steep curved surfaces, reduce calculation time and improve planning efficiency. Compared with the potential computational bottlenecks of other CAM software in machining complex curved surfaces, UG exhibits better response speed and processing capability. Flexibility is manifested in its powerful strategy customization and parametric control functions. Users can dynamically adjust cutting parameters, tool entry and exit modes, and region division rules according to material characteristics, part geometric constraints and specific process requirements[3]. This rule-based dynamic path adjustment capability enables UG to meet the agile machining needs of multi-variety and small-batch complex parts.

2.2. Application of UG in the machining of complex parts

In the field of complex part machining, UG software has become a core tool for solving high-difficulty manufacturing tasks by virtue of its powerful integrated modeling, simulation and machining capabilities. Complex parts usually have highly special-shaped surface structures, strict tolerance requirements and complex material removal areas, and traditional machining methods are often difficult to balance efficiency and precision. Through its deeply integrated CAD/CAM functions, UG software can accurately calculate and optimize tool paths with the support of physical simulation verification, providing a theoretical support and technical implementation platform for the machining path planning of such parts.

Taking aero-engine blade parts as an example, machining faces key challenges such as easy deformation of thin walls, high precision requirements for free-form surfaces, and complex tool accessibility and interference checking. Through its advanced surface machining module, UG software can accurately calculate the contact points between the cutting tool and the blade profile surface, and automatically generate smooth and continuous tool paths that conform to curvature changes, effectively reducing cutting vibration and ensuring surface quality. At the same time, the multi-axis linkage tool axis control function can intelligently plan the tool posture, effectively avoid the risk of interference with adjacent blades or fixtures, and assist in optimizing cutting parameters through the cutting force prediction model to reduce thin-wall deformation.

3. Tool path planning methods for NC machining of complex parts

3.1. Basic principles of tool path planning

Tool path planning is the core link of NC machining for complex parts. In essence, it is to scientifically plan the spatial motion trajectory and state of the cutting tool according to the part geometry, material characteristics, machining requirements and machine tool constraints. Its basic principle is to generate an efficient, interference-free tool path sequence that meets machining quality requirements through mathematical modeling and algorithm design. This process directly determines the material removal efficiency, machining accuracy, surface quality, as well as the service life of machine tools and cutting tools .

Tool path generation is the primary task of path planning, involving the calculation and connection of tool contact points. Its goal is to enable the cutting tool to efficiently remove materials along a predetermined path on the premise of avoiding collisions with the workpiece and fixtures. Interference avoidance relies on accurate geometric model collision detection algorithms to ensure that the cutting tool is in a safe space at any position and posture. Cutting parameter optimization runs through the entire process, which requires a comprehensive consideration of key parameters such as spindle speed, feed rate, cutting depth and cutting width. The selection of these parameters must strictly follow the principles of metal cutting mechanics, balancing the relationship between material removal rate and cutting force, cutting heat, so as to suppress vibration, reduce deformation, control surface quality and extend tool life. An excessively high feed rate improves efficiency but may lead to deteriorated surface roughness or tool chipping, while excessively low parameters may improve surface quality at the cost of machining efficiency.

3.2. Key technologies of path planning based on UG

The realization of efficient tool path planning in the UG environment relies on its integrated geometric processing core and physical simulation module. Based on the principles of computational geometry and metal cutting mechanics, this paper constructs a dual-constraint framework for path optimization: the geometric level ensures that the tool path fully covers the machined surface without residue, and the physical level controls the fluctuation of cutting force to reduce tool vibration. This framework realizes the integration of the following key technologies through the UG/NX CAM system.

The contour layered machining strategy adopts layered tool path generation technology, dynamically adjusting the Z-direction cutting depth according to the surface curvature characteristics. The "Z-Level" module of UG automatically calculates the optimal layer height through the offset surface algorithm, making the spacing between adjacent tool paths meet the residual height threshold. Spiral cutting technology uses the principle of continuous curvature path planning to generate spiral tool paths without tool marks through the "Spiral" function of UG. Its core algorithm adopts the Archimedean spiral equation and surface parametric mapping to realize the continuous radial offset of the cutting tool from the cavity center to the outer edge, reducing the proportion of non-cutting travel to below 5%. Aiming at multi-feature composite parts, the region segmentation strategy implements automatic feature recognition through the "Face Milling" module of UG. It performs machining region clustering based on the Boundary Representation (B-rep) model, establishes a feature association network combined with graph theory methods, and intelligently divides independent machining subdomains.

4. Optimization and simulation of tool path planning

4.1. Path optimization algorithms

Path optimization algorithms are the core technologies to improve the efficiency of NC machining, whose theoretical basis is derived from the combinatorial optimization and intelligent computing principles in operational research. Two representative methods, namely the genetic algorithm and the ant colony algorithm, are mainly adopted for path optimization. The genetic algorithm simulates the natural selection process, iteratively optimizing the path population through operators such as selection, crossover and mutation, and has a strong global search capability. The ant colony algorithm imitates the foraging behavior of ants, and uses the positive feedback mechanism of pheromone to find the shortest path, which performs excellently in dealing with discrete optimization problems. Both algorithms are committed to solving the key problems of minimizing tool non-cutting travel and improving cutting continuity, and their mathematical essence is to solve the optimal or approximate tool motion sequence under the condition of satisfying geometric constraints.

To implement path optimization in the UG software environment, it is necessary to make full use of its open secondary development interface and powerful geometric engine. In this paper, the 3D process model of complex parts is first constructed in UG, and the initial machining strategy is set. Then, the optimization logic of the genetic algorithm or ant colony algorithm is embedded into the post-processing process of UG. Specifically, the genetic algorithm converts the tool path into chromosomes through coding, takes the non-cutting travel length and cutting continuity as the fitness function, and realizes automatic iterative optimization on the UG platform. The ant colony algorithm needs to establish a path node network model in the machining coordinate system of UG, dynamically adjust the path selection probability through the pheromone accumulation and volatilization mechanism, and finally output the optimized tool path. The effectiveness of the algorithms is highly dependent on UG's accurate geometric calculation and collision detection capabilities.

4.2. Machining simulation and verification in the UG environment

Machining simulation in the UG environment is a key link to verify the rationality and safety of tool path planning, whose theoretical basis lies in the virtual mapping of the physical machining process by digital twin technology. This paper elaborates on the standard process of machining simulation using UG NX software, which starts with the dynamic simulation of the tool path. After the tool path is generated in the UG CAM module, the integrated visual simulation tool can accurately reproduce the 3D motion trajectory of the cutting tool relative to the workpiece. This dynamic simulation not only intuitively displays the cutting process, but also clearly reflects the detailed actions such as tool feeding, retracting and reversing, providing a direct basis for the preliminary evaluation of path continuity and the avoidance of non-cutting travel.

Collision detection is the core link of simulation safety verification. Based on accurate geometric and kinematic models, the UG system can automatically detect potential interference and collision risks between the cutting tool, tool holder, machine tool spindle, fixture and the workpiece or machine tool body. The system identifies and highlights any possible collision areas by real-time calculation of the spatial position relationship of the envelope of each moving part under the preset path. This function is particularly important for parts with complex structures and limited machining space, and can effectively prevent costly equipment damage accidents in actual machining. This paper emphasizes that thorough collision detection should cover all possible combinations of machine tool motion axes and tool change processes.

5. Conclusions and prospects

The effectiveness of the tool path optimization algorithm studied in this paper is highly dependent on the underlying interface and computing environment provided by UG software, and it may face computational efficiency bottlenecks when processing ultra-large complex models or conducting high-precision multi-physics field coupling simulation. The research on UG-based tool path planning should focus on breaking through in the following directions: first, deepen the application of intelligent technologies in path planning, explore the potential of machine learning and deep learning algorithms in the adaptive matching of cutting parameters, machining state prediction and real-time path optimization, so as to improve the autonomous decision-making ability of the system. Second, strengthen the research on path planning algorithms in the multi-axis machining environment, focus on solving key problems such as smooth optimization of tool axis vector, avoidance of singular points of rotating axes and prediction of machining dynamic stability, so as to realize high-quality and high-efficiency machining of complex spatial curved surfaces. Third, promote the deep integration of CAD/CAM/CAE, build a full-process closed-loop optimization system covering design, process planning, simulation verification and actual machining, and fundamentally improve the efficiency and reliability of complex part manufacturing.

Fundings

Scientific research project of Sichuan Institute of Industrial Technology entitled: "Research on Tool Path Planning for NC Machining of Complex Parts Based on CAM", Project No. GKY24S03.

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References

[1] Zhang Xinyun, Wang Zexiao, Cao Yan, et al.Research on NC machining parameters of aeroengine casing [J].manufacturing technology and machine tools, 2024 (8): 9-15.

[2] Liu Ying.Development of CAD/CAE system based on UG [J].China Metalforging Equipment & Manufacturing Technology, 2025 (5).

[3] Zhang Hao, Zhang Shuaishuai, Lai Xinjian, et al.Five axis programming and processing technology of pump body parts based on UG [J].Mechanical&electrical engineering technology, 2025, 54 (18).