Research on Thermal Topology Design Method of Spindle Based on HCAM

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Abstract. Spindle thermal error is one of the key factors in the machining accuracy of CNC machine tool. In order to reduce the thermal error of the spindle and improve the machining precision of the CNC machine tool, the idea of the thermal topology design based on the hybrid cellular automaton method (HCAM) is proposed. In this paper, the existing research results of hybrid cellular automaton are summarized, and the main achievements of domestic and foreign research work are analysed and reviewed from the aspects of structural topology optimization. Finally, the realization and prospect of HCAM self-optimizing thermal topology design method for spindle are presented.

1. Introduction

A large number of researches have shown that in the factors that affect the machining accuracy, the thermal error of the spindle is the biggest error source of precision machining machines such as CNC machine tool [1]. Spindle is an important component of the machine tool, which is directly involved in processing. The thermal error control problem of spindle is very important for the improvement and maintenance of machining precision for machine tool. It has been a hot topic for domestic and foreign scholars [2-4].

Spindle thermal design problems mainly come from the engineering field; meanwhile, the self-optimization phenomenon exists in nature, such as the distribution of different wood in the trunk and the distribution of different material in the animal bones, which are all worth studying in thermal design. Hybrid Cellular Automaton Method (HCAM) is a biomarker topology optimization method proposed by Tovar [5] bone remodelling biology process (shown in Figure 1 and Figure 2). According to the theory of bone reconstruction, simulating the bone remodelling process and reshaping the internal structure of the skeleton to have a uniform strain energy density. According to the theory of bone reconstruction, CA (Cellular Automaton) method and FEM (Finite Element Method) are combined. The CA cells record the material distribution in the design space. The FEM calculates the material density. The results of the changes which are caused by the CA cells state change through a one-to-one correspondence mapping to the finite element model. The method is simple and easy to understand, the convergence is good, the calculation efficiency is high, the numerical instability is reduced, and the structure topology and even the solution to the multi-objective problem can be solved automatically.
2. Research status of topology optimization design based on HCAM

The structural design and optimization of the continuum structure of the mechanical structure has been a major problem in the automatic design of the structure. Nowadays, the frequently-used continuum topology optimization algorithms are Homogenization Method, Variable Density Method, Progressive Structure Optimization Method and CA method and so on. HCAM [5] is based on Tovar's theory of bone reconstruction, coupling CA method and FEM. A topological optimization bionic design method is proposed to solve the problem that CA method does not solve the global analysis of field state. HCAM uses the FEM analysis to evaluate the field state (strain energy), that is, using FEM to calculate the strain energy as the state information of CA. This method is easy to understand, and has good convergence, high computational efficiency and reduces numerical instability. Those multi-objective problem solving could provide new analytical ideas and technical means [6,7] for the effective structure of the topology optimization design. In recent years, Tovar and other scholars have also combined the energy absorption control method [8], weighted multi-objective method [9], harmonic vibration load method [10] with HCAM application successfully in the vehicle anti-collision design, thin-walled tube structure optimal design, the energy collector shell and the outdoor air-conditioning cover [11] are optimized even on military projects such as multi-material explosion-proof armour plate optimization design [12].

At home, Professor Chen [13] studied the structural topology optimization based on HCAM and the method of solving the topology of stress constraint and displacement constraint. By employing the penalty function method, the strain energy density target value, to achieve the organic combination with the CA local rules. Professor Guo [14] et al. proposed a method for topology optimization of multi-space continuum structures based on HCAM for large-deformation nonlinear structural topology optimization problems. In 2011, a hybrid cellular automaton framework optimization method was proposed. The method was based on the application of strain and multi-domain topology optimization algorithm to HCAM. As shown in Figure 2, the research on vehicle crashworthiness in the case of large deformation is studied, including transient, non-linear finite element structure analysis and local control rules on the cell [15]. Wang [16] et al. implemented an optimization design on the aluminium alloy front impact beam structure by HCAM to optimize calculation model based on explicit dynamic finite element analysis software. Dr. Cui [17] applied HCAM to the flexible mechanism design with interval parameters. The local rules were used to control the distribution of materials in the design domain and converge with less iteration and finally got the structure topology optimization design results. Ni[18] et al. focused on the target of minimization of strain energy and the maximization of mutual strain energy, constrained by the structure volume, proportional controlled by local control law and applied HCAM to simple two-dimensional compliant mechanism (displacement inverter) topology optimization, effectively eliminating the different nature of the objective function in the order of magnitude difference.
The literatures’ research show that HCAM has been applied in the optimization design of different product topology under stress and displacement constraints. It has high convergence, high efficiency, stable numerical calculation and other obvious advantages. Its development is rapid and has strong vitality and application prospect. Therefore, the application of HCAM based on the theory of bone reconstruction will provide a new bionic method for thermo-design and optimization of the spindle.

3. Realization of HCAM self-optimizing thermal topology design method for spindle

The difference between bone and general engineering materials is that it is constantly changing as a biological material. From the perspective of mechanics, bones are a functional adaptive structure, and its growth and reconstruction are related to the mechanical environment. Through the precipitation and absorption in different parts, the optimal structural form of the mechanical environment is formed [19], that is, self-optimizing function (skeletal function adaptive rule). Based on the theory of bone reconstruction and the theory of structural optimization, the self-optimizing design model is established based on volume ratio, heat flux density and local temperature. The local evolution rule is established. The CA cells and the finite element model’s grids have one-to-one correspondence. It firstly constructs a single component, a single optimization space optimization design method, and then extended to multi-component integration system and multi-space domain optimization. And the optimization results are compared with the spindle prototype. Finally, the optimization model and algorithm are validated on the thermal equilibrium test platform.

The main process of using HCAM spindle self-optimizing bionic thermal topology design algorithm is as follows:

1. Based on the fluid-temperature-structure field coupling mathematical model, the parameters such as design area, material property and thermal load are defined, and the design value $x^{(0)}$ is initialized.
2. The solid isotropic penalty microstructure model based on variable density method is employed to design the domain material parameterization. The penalty factor is used to punish the intermediate density value. And the heat conduction coefficient $E^{(t)}$ of each element in the model is expressed by the exponential function of the unit relative density $P$, which is

$$E^{(t)} = x^{(t)} p E_0 \quad (p = 1)$$

where, $E_0$ is the relative thermal conductivity of the material which value is 1. So that the intermediate density values converge to both ends of 0/1, and the topological optimization model of continuous variables can approach the optimization model of 0-1 discrete variables.

3. Calculate the field variable $S(x^{(t)})$ with FEM, and then assign it.

4. The material part of the design field is determined according to the local PID feedback control rule of HCAM. The change of the set value $S$ of the state field variable $S_{avg}$ and the set value $S$ of the state field variable is minimized to calculate the variation $\Delta x$ of the design variable. To avoid numerical instability, set the upper and lower limits for each iteration design process.

5. In the process of iterative self-optimizing thermal design, the local control rule is applied to update the design variable $x^{(t+1)}$, and the change of the design variable is used as the convergence criterion to judge whether the minimum difference is set for the given difference or not. Please see Figure 4.

6. Check convergence, when the convergence criteria is met, the final topology structure will be got, or return to step 3 to continue to run.

7. Through the comparison with the original design of the program, you can get a better design. Figure 3 is a flow.

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**Figure 4.** Structure Thermal Topology Self-Optimizing Algorithm Process of Spindle
4. Conclusions

Spindle, as one of the key component of CNC machine tools, its thermal error control has a very important role in improving the machining precision for CNC machine tool. HCAM is a method can be used to solve the topology design and optimization problem of spindle structure thermo-design in the future, and decrease the thermal error of spindle. It is useful for precision machine tool designer in research, analysis, decision-making, and any other related activities.

Acknowledgments

This research was financially supported by National Natural Science Foundation of China (No. 51605253), Zhejiang Provincial Natural Science Foundation of China (No. LY16E050011) and Quzhou Science and Technology Planning Project (2016Y003 & 2015Y007).

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