Design Method of Function-Structure Integrated Lattice Structure

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Abstract. Structure lightweight has always been a hot topic in the field of engineering. Lattice structure has characteristics of light weight, high specific stiffness and high specific strength because of its high porosity and low relative density. It has been widely used in structural lightweight design. In addition, lattice structure has broad application prospects in advanced industrial equipment, due to the potential of anti-vibration, anti-impact, heat transfer and heat dissipation, zero/negative thermal expansion, electromagnetic wave absorption, sound absorption and noise reduction. In this paper, a design method of function-structure integrated lattice structure is proposed, topology optimization and variable density lattice filling technology are studied, the research methods of multi-functional characteristics of lattice structures are discussed, and the related simulation and experimental methods are introduced, which is of certain reference significance to the development of technology in this field.

Key words: lattice structure; topology optimization; lightweight structure; integration of function and structure

1. Introduction
The technology of structure lightweight aiming at reducing equipment self-weight, reducing driving energy and improving carrying capacity has always been a hot topic in the fields of engineering machinery, aerospace, rail transit and so on[1]. Lattice structure has good properties such as lightweight, high specific stiffness and strength because of its high porosity, low relative density and periodic distribution [2]. It has been well applied in structural lightweight. In recent years, researchers have gradually found that lattice structure has many functions such as anti-vibration and anti-impact, heat transfer and heat dissipation, electromagnetic wave absorption, sound absorption and noise reduction, zero/negative thermal expansion, etc. [3]. Lattice structure provides some new ideas on the development of multifunctional materials and integrated design technology. It is of great significance to study the basic theory, simulation and experiment of the multifunctional characteristics of lattice structures.

2. Design of function-structure integrated lattice structure
An design method of function-structure integrated lattice structure is proposed, which included three parts: topology optimization and variable density lattice filling, multi-functional characteristics of lattice structure, simulation and experimental verification. The flow chart of the function-structure integrated lattice structure is shown in Figure 1.
3. Topology optimization and variable density lattice filling technology

3.1. Structural Topology Optimization

The topology optimization is an important method for lightweight structural design. A given product structure, with certain load conditions, constraints and performance indicators, is optimized and analyzed to remove redundant materials and retain key materials, so as to reduce the relative density of materials and achieve the goal of lightweight\[4\].

Common topology optimization software includes OptiStruct, Tosca, Top 3D, etc. The continuum structure is topologically analyzed to obtain the material density distribution parameters, which provide the basis for lightweight design and variable density lattice filling.
3.2. Lattice Structure and Cell Design

Lattice structure is also called multicellular structure or artificial periodic structure. According to cell structure and composition rules, it can be divided into: (1) two-dimensional lattice structure, such as grid structure, honeycomb structure (square, hexagon), etc.; (2) three-dimensional lattice structure, such as truss structure, sandwich structure (inclined column, pyramid), cubic lattice structure (face-centered FCC, body-centered BCC), etc.; (3) other complex lattice structure, such as wire-wound structure, etc. [5].

In practical application, the lattice type should be selected and lattice size should be designed according to different working conditions. The basic unit of lattice structure is lattice cell. The analysis and design of single cell is the basis of the follow-up research.

For two-dimensional lattice structures, Gibson method is often used to analyse lattice cells. The stress-strain equation is established according to the compatibility relation of deformation, and the equivalent elastic parameters of lattice structure, named Gibson formula [6], are calculated.

For example, Gibson’s formula for equivalent elastic properties of square honeycombs:

\[
\begin{align*}
  x &= 2 \frac{t}{a} \left( 1 - \frac{1}{2} \frac{t}{a} \right) \\
  \frac{E_s'}{E_s} &= \frac{E_s'}{E_s} = \frac{t}{a} \\
  \frac{G_{12}'}{E_s} &= \frac{G_{12}'}{E_s} = \frac{1}{16} x^3 \\
  \nu_{12} &= \nu_{21} = \nu_s = \frac{t}{a} = \frac{1}{2} \nu_s x
\end{align*}
\]

Among them, the elastic modulus, shear modulus and Poisson’s ratio of cell are expressed as functions of relative density \( x \), and the elastic modulus and Poisson’s ratio of solid material of cell wall are expressed by \( E_s \) and \( \nu_s \), and the cell size and rod size are expressed by \( a \) and \( t \).

For the three-dimensional lattice structure, the relationship between relative density \( x \) and cell size \( a \) and rod size \( t \) can be expressed by the ratio of lattice cell volume \( V_{\text{entity}} \) and cell outline volume \( V_{\text{outline}} \).

Three-dimensional software such as Creo, UG and SolidWorks are often used to design and model lattice cells.

The manufacturing constraints of lattice structure are analyzed according to the characteristics of augmented material manufacturing process, which provides a basis for cell structure design, cell type and cell size optimization.

3.3. Variable Density Lattice Filling Technology

Lattice structure is a good material for lightweight design because of its porous and lightweight characteristics. Combining lattice structure with topology optimization technology leads to variable density lattice filling technology.

Because of the complex spatial structure of three-dimensional lattice cells and the variable density arrangement, it often takes a lot of time and is difficult to operate by using existing three-dimensional software to model. Therefore, based on Pro/Toolkit function library developed by REO or UG, a parameterized automatic assembly aided program for variable density lattice structure is developed. Each lattice cell is defined and assembled in the form of cell elements, and finally a variable density lattice structure model is formed [7].

The flow chart of variable density lattice structure modeling is shown in Figure 2.
4. Research methods of multifunctional characteristics of lattice structures

The multifunctional characteristics of lattice structure mainly include static, dynamic, thermodynamic, acoustic and other characteristics.

4.1. Static characteristics

Static and mechanical properties of lattice structures include tensile, compressive, bending and torsional properties.

For the two-dimensional lattice structure, the simulation results are fitted by using MATLAB, and the fitting formula is obtained, and the Gibson formula is modified. Based on the modified Gibson formula, the equivalent elastic model, the equivalent Poisson's ratio and the equivalent shear modulus are calculated, and the two-dimensional elastic constitutive relationship is established.

For three-dimensional lattice structures, the equivalent elastic constitutive relation is established [8]. For the body-centered cubic lattice structure, based on the method of strain energy equivalence, the formula for calculating the equivalent parameters in the elastic constitutive relation of lattice structure is obtained as follows:

\[
\sigma_{ij} = \begin{bmatrix}
E^H \left[ \frac{1 + \nu^H}{2} \right] & E^H u_i^0 & E^H u_j^0 \\
\frac{1 + \nu^H}{2} & \frac{1 - 2\nu^H}{2} & \frac{1 + \nu^H}{2} \\
\frac{1 + \nu^H}{2} & \frac{1 - 2\nu^H}{2} & \frac{1 + \nu^H}{2} \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{23} \\
\sigma_{31} \\
\sigma_{12} \\
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\varepsilon_{23} \\
\varepsilon_{31} \\
\varepsilon_{12} \\
\end{bmatrix}
\]
The constitutive relation, mechanical equilibrium equation and equivalent parameter expression of lattice structure material are obtained, by means of theoretical analysis and mathematical derivation, which are the key to study the static characteristics of lattice structure.

4.2. Kinetic Characteristics
The dynamic performance of lattice structure includes vibration, impact and fatigue.

(1) Vibration of lattice structures
Based on Reissner sandwich plate theory, the vibration equation and natural frequency solution formula of lattice truss sandwich plate are established[9].

The thin shell theory assumes that the strain and stress obey Hooke's law. Based on Love's thin shell theory, the natural frequency equation and the solution formula of natural frequency are established[10].

Based on the equilibrium differential equation of elastic body in space, the differential equation of elastic surface and the solution formula of natural frequency of thin plate lattice structure are established.

Vibration frequency response characteristics of several different lattice structures should be discussed, natural frequencies and modes should be calculated, and the effects of lattice type, cell size and relative density on anti-vibration performance should be studied.

(2) Impact of lattice structures
The three basic equations of lattice structure subjected to impact are established. The physical model of explosive shock is built, and the constitutive relation of structure and the propagation theory of shock wave under explosive shock are studied[11].

The dynamic response of several different lattice structures under a certain impact load should be studied. The deformation and energy absorption should be calculated. The influence of lattice type, cell size and relative density on impact resistance should be analyzed.

4.3. Thermodynamic properties
Thermodynamic properties of lattice structures include heat transfer, heat dissipation, zero/negative thermal expansion, etc.

(1) Heat transfer and heat dissipation of lattice structure.
The lattice structure has high porosity, high specific surface area and good permeability, which is convenient for convective heat transfer and can achieve good heat transfer and heat dissipation effect[12].

The physical model and thermodynamic equation of lattice heat transfer and heat dissipation should be established. The thermal stress distribution of different lattice structures under different thermal loads should be discussed. The effects of lattice type, cell size and density distribution on heat transfer and heat dissipation performance should be studied.

(2) Zero/negative thermal expansion lattice structure.
Zero/negative thermal expansion structure can be formed by using different thermal expansion coefficients of different materials to design certain material ratio and micro-structure, which can realize the regulation of thermal expansion [13]. The thermal expansion physical model of composite
rod structure should be established, the thermal deformation mechanism under thermal load should be analyzed, the connection modes of rods with different materials and the filling process of zero/negative thermal expansion lattice cells should be studied. The thermal deformation laws of different zero/negative thermal expansion structures under different temperature loads should be discussed. The effects of lattice type, bar shape, connection mode and material properties on the zero/negative thermal expansion characteristics of structures should be studied.

According to the thermal expansion coefficients of different materials, with specific modulus and multiple symmetry as constraints, by topological optimization, the microstructures could be designed to achieve zero/negative thermal expansion[14], as shown in Figure 3.

4.4. Sound transmission and noise reduction characteristics
The sound absorption and noise reduction performance of lattice structure includes sound transmission/absorption, noise reduction and so on.

When noise propagates in rods, nodes and panels of lattice structures, sound energy dissipates in the form of heat energy, which can absorb sound waves and reduce noise [15].

The physical model of sound propagation in lattice structure should be established. Then, the phononic crystal of lattice structure should be designed. The sound propagation law in different lattice structures should be analysed, and the effects of lattice type, cell size and density distribution on sound transmission characteristics, phononic crystal band gap characteristics and noise reduction characteristics should be studied.

5. Simulation and experimental methods
According to the different functional characteristics of lattice structure, different modeling and simulation software are often used. Finite element software ANSYS is often used to analyze static and dynamic loads of lattice structures; Nastran is often used to analyze the frequency response characteristics of lattice structures; ANSYS and Thermo-Calc are often used to analyze the thermodynamic characteristics of lattice structures; MSC is often used to analyze the sound transmission and absorption characteristics of lattice structures.

For example, the deformation and displacement of two-dimensional honeycomb structure and three-dimensional cubic lattice structure under tension, compression and torsion loads were simulated and analyzed by finite element software ANSYS, and the compressive and bending properties of lattice structure are analyzed [16], as shown in Figure 4.

Figure 3. Zero/negative thermal expansion microstructure

(a) hexagonal honeycomb lattice (b) body-centered cubic lattice
Figure 4. Three-point bending force simulation of lattice structure

On the basis of numerical simulation analysis of lattice structure and specific working conditions, the corresponding experimental platform is built to verify the functional characteristics of lattice structure and obtain experimental data. Finally, through data analysis and mining of theoretical, simulation and experimental results, the influence of lattice type, cell size and density distribution on functional characteristics will be summarized, and the coupling relationship between functional characteristics is analyzed. Then, the optimization design of lattice cell configuration, cell size, density distribution and other structural parameters is carried out continuously to improve the lattice structure performance and realize the lattice structure design of integration of work and structure.

6. Conclusion

In this study, a design method of functional-structural integrated lattice structure is proposed, which includes three parts: topology optimization of lattice structure and filling of variable density lattice, multi-functional characteristics of lattice structure, simulation and experimental verification. Three research methods: theoretical analysis, numerical simulation and experimental verification, is combined, the influence rules of parameters is summarized by data analysis, and structural parameters is optimized. By filling with variable density lattice, the product structure is designed to be lightweight. At the same time, it also had multi-functional characteristics, such as anti-vibration, anti-impact, heat transfer and heat dissipation, zero/negative thermal expansion, etc. It realized the lattice structure design of power structure integration to meet the high performance requirements of industrial equipment. The research in this paper is meaningful for the development of the design of functional-structural integrated structure. However, The disadvantage is that some theories and techniques involved in this paper are still immature and need to be further studied.

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