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Research Article

Optimal Design of Periodic Honeycomb Plate with Unit Cell Structure Based on Genetic Algorithm

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Composite honeycomb sandwich plates have been widely used in aerospace, ships, construction bridges, machinery, stationery, and other industries. In order to improve the performance and configuration, taking the structural dynamic characteristics of periodic honeycomb plate as the research object, a structural optimization design method based on natural frequency and stiffness was proposed with the goal of weight reduction. The geometric parameters of the structure system were trained by the multiobjective optimization genetic algorithm (MOGA), and the Pareto optimal solution of variable combination was obtained. This paper presented a decoupling method for complex system optimization design based on dynamic performance from the perspective of basic unit, which could solve the coordination problem of vibration stability and weight reduction in periodic honeycomb plate structure optimization design. It has reference significance for the similar composite material frame base structure design.

1. Introductions

The superior performances of advanced materials are shown in strength, stiffness, fatigue resistance, material designability, and so on. Composite structural materials are widely used in various fields such as aviation, aerospace, shipbuilding, automobiles, medical treatment, and construction. It has played an important role in improving the performance of the structure, reducing the quality of the structure, and optimizing the appearance of the structure. Porous materials are commonly found in nature, such as animal and human bones, trees, flower stems, and honeycombs. They have various functions such as structure, shock absorption, cushioning, sound absorption and heat insulation, and filtration. Porous materials improve the mechanical properties of the material by concentrating the substances in the place where the force is applied [1, 2].

The honeycomb sandwich structure comes from nature and is a special structural form created by humans from the honeycomb. The honeycomb sandwich structure is composed of three parts: the upper panel, the lower panel, and the honeycomb sandwich core. Different materials and sizes can be selected according to actual needs. At present, the most common materials for the upper and lower panels of the sandwich panel are mainly aluminum alloy, carbon fiber, FRP, fiber, etc., while the honeycomb core is mainly made of aluminum honeycomb [3]. Compared with other structural plates, the strength of honeycomb panels is obviously improved with the same quality. Specifically, the regular hexagon structure honeycomb has the characteristics of high strength, light weight, heat insulation, sound insulation, and noise reduction. Regular hexagonal honeycomb structure is also very common in nature. Because each side of the hexagonal structure interacts, the external forces from all directions can be well dispersed, showing outstanding mechanical properties.

In the design of medium-thick hexagonal honeycomb sandwich panel, the improved multiobjective particle swarm genetic algorithm can be applied to structure optimization. The total weight and deformation deflection are taken as objective functions. Under the constraints of strength and size, through the advantages and disadvantages of particle groups, the optimal combination of various geometric parameters is obtained [4]. The structure of each layer of multilayer multiphase nanocomposites is complex; so, an equivalent mechanical equation is established. The effects of temperature, humidity, viscosity, and magnetic properties on deflection deformation were calculated by differential volume method (DCM) combined with the Newmark method [5]. The multiobjective wolf colony algorithm is also an effective optimization algorithm. The UAV composite foldable flexible wing cover is made of composite honeycomb sandwich material. Based on population density, the multiobjective wolf colony algorithm realizes the optimal design of the surface structure of the folding inflatable flexible fan, which effectively improving the strength of honeycomb sandwich wing cover layup structure [6]. Aiming at the nonlinear elastic properties of the flexible chiral honeycomb core, the genetic algorithm is used to optimize the structure and geometry of the chiral hexagonal honeycomb, which can maintain a good elasticity of Young's modulus and Poisson's ratio unchanged under large deformation [7]. Ahmad et al. studied the thin-walled characteristics of Nomex honeycomb composite (NHC) honeycomb hexagon. The effects of material processing technology and processing tools on surface quality are analyzed [8]. Using the method of numerical analysis, qualitative and quantitative analysis of the internal geometric structure and size of the honeycomb structure were carried out. As a result, the optimal states of the elastic characteristics of the honeycomb structure under large and small deformation were obtained [9]. The material of the aircraft fuselage struts is a composite material of polymer honeycomb structure. The crashworthiness of the aircraft fuselage strut structure has been optimized, in which the single-objective optimization and multiobjective optimization models are, respectively, applied for the parameters of different properties. Discriminate the influence weights of various element structures on the structural performance [10]. For the aluminum honeycomb sandwich structure, the combined method of numerical analysis and experiment is used to study the influence of various structural parameters and geometric parameters on the mechanical properties. The results show that the element wall thickness in the structure is the parameter that has the greatest impact on performance, followed by element size. In addition, the best combination of input parameters is found by Taguchi grey relational analysis [11]. The honeycomb structure has been studied from many aspects. However, if advanced and intelligent optimization algorithms can be applied in honeycomb analysis from the multiviews of system mechanical properties, volume, weight, inherent characteristics, etc. The honeycomb would be improved more accurately, quickly, and conveniently.

The main failure mode of the honeycomb sandwich structure is the loss of stability. In order to ensure the safety of the structure, it is necessary to analyze the stability of the sandwich structure. The stability of the structure mainly depends on the structure stiffness, which is mainly related to the mechanical properties of the material and the geometric characteristics of the structure. The goal of structural design is to lighten as much as possible on the premise of meeting the design requirements. For example, the lightweight of spacecraft and automobiles can greatly reduce fuel and energy consumption, which is of great significance. Specifically related to the honeycomb sandwich structure, the plate thickness should be small, the core grid size should be large, the core layer thickness should be thin, and so on. However, such a design can easily cause stability problems after the structure is loaded, which is not allowed in actual engineering.

In order to ensure the safe and reliable of the honeycomb sandwich structure, its mechanical properties are necessary to be deeply studied. In this paper, the stability of mechanical properties of honeycomb plate is analyzed, and the advanced optimization algorithm is used to obtain the coordination method of material lightness and stability, so as to realize the optimal configuration of structural parameters.

2. Honeycomb Sandwich Plate Model

The honeycomb plate is a kind of sandwich plate similar to a sandwich structure, which is made up of two thin and high-strength plates on the surface and a thick and light honeycomb core in the middle through gluing or welding. As shown in Figure 1. In general, the thickness of the middle honeycomb sandwich layer is many times higher than the thickness of the plate, and the honeycomb core layer has a special hollow structure. Therefore, the honeycomb sandwich plate has a relatively low density compared with the solid structure. The material of the honeycomb plate is usually made of metal or composite material with higher specific strength, and the form of the honeycomb core grid can be hexagonal, rectangular, corrugated, diamond, etc. Since the regular hexagonal structure honeycomb uses less materials and is easy to process and manufacture, it is widely used in various fields.

Since the honeycomb core mainly bears the in-plane shear stress, and the in-plane stress is very small compared with the upper and lower panels, when the load is perpendicular to the panel, the in-plane compressive stress caused by bending is mainly borne by the upper panel, and the tensile stress is borne by the lower panel. The honeycomb core layer is much thicker than the panel, which greatly increases the span between the upper panel and the lower panel, so that bending stiffness of honeycomb plate can be effectively improved. From the material mechanics, it can be seen that the bending stiffness is not only related to the elastic modulus of the material but also the moment of inertia that is associated with the distance from the middle surface. In honeycomb plate, the farther surface from the middle surface bears the stronger bending stiffness. Therefore, the bending stiffness of the honeycomb plate is not much different from that of the solid plate with the same thickness, but it can reduce the weight by more than 70%.

2.1. Equivalent Stiffness. The equivalent plate theory is to equate the overall honeycomb sandwich plate to an isotropic material plate of different thickness. Then according to the equal stiffness and equal mass between the sandwich plate and the equivalent plate, the elastic modulus, thickness,

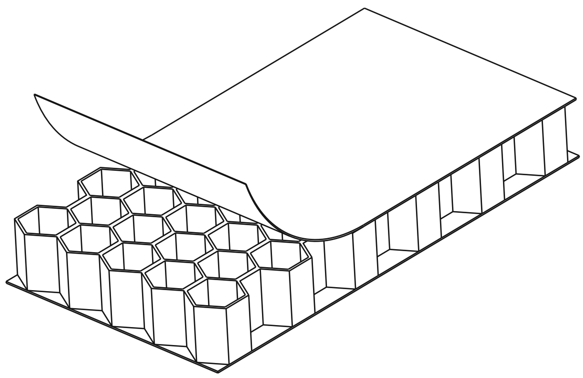


Figure 1: Microsatellite appearance structure.

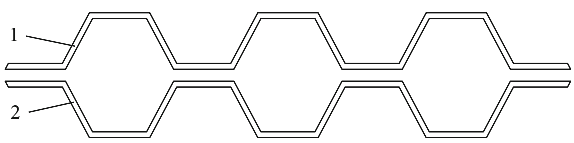


Figure 2: Bonding mode of adjacent plates.

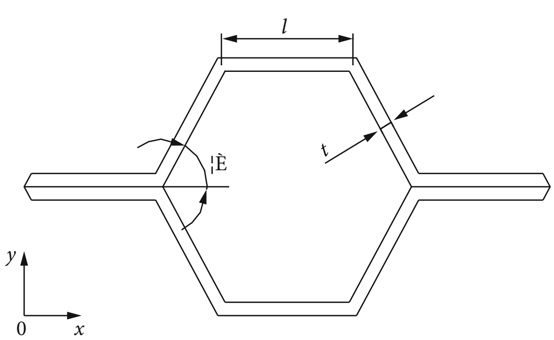


Figure 3: Unit cell structure of periodic honeycomb plate.

density, and other relevant parameters of the equivalent plate are deduced. This theory is easy to implement, but it cannot reflect the influence of honeycomb core shape on the overall performance of the sandwich plate, and the specific size of the honeycomb core grid cannot be determined [12, 13].

Due to the small thickness of the side wall of the honeycomb core, according to the buckling instability theory of the rectangular thin plate, the flat compression deformation process of the side wall of the honeycomb core can be equivalent to the instability process of a rectangular thin plate simply supported on four sides under unidirectional compression, and the displacement of the honeycomb core wall during the deformation process is much smaller than the height of the honeycomb core. Therefore, the deformation process of the honeycomb core wall is assumed to be a small deformation problem. Honeycomb plate with unit cell is shown as in Figures 2 and 3. In the manufacturing of honeycomb plate core, the material is folded into corrugated shape, and then the adjacent corrugated plates are reversely laminated and welded at the contact sides [14]. Therefore, if the thickness of the corrugated plate at the nonconnect side is t, and the thickness at the connect part is 2 t.

The deflection differential equation is

$$D\nabla^4\omega = f_x \frac{\partial^2\omega}{\partial x^2} + f_{xy}\frac{\partial^2\omega}{\partial x\partial y} + f_y \frac{\partial^2\omega}{\partial y^2}, \tag{1}$$

where ω is the displacement (i.e., deflection) of each point on plate middle surface under load $f(x, y)$ is the distributed load of the plate, and D is the bending stiffness of the plate,

In the process of flat pressing of the honeycomb plate, taking the x compression direction as the positive direction, and $f_{xy} = f_y = 0$ is brought into equation ((1)), the buckling governing equation of the honeycomb plate is obtained as

$$D\nabla^4\omega + f_x \frac{\partial^2\omega}{\partial x^2} = 0, \tag{2}$$

$$D = \frac{Et^3}{12(1-\nu^2)}, \tag{3}$$

where E is the elastic modulus of the plate material, ν is the Poisson's ratio, and t is the plate thickness.

The honeycomb sandwich plate is equivalent to an isotropic shell element with different thickness from the original sandwich plate, which can simultaneously bear the shear, bending, and torsional loads on vertical plate surface and the tension, compression, and shear loads in the plane. Among them, as a curved plate, it conforms to the Kirchhoff hypothesis of a thin plate with small deflection, and its stiffness D is obtained [15].

According to the force balance condition of a single honeycomb cell in the uniform tension state of the equivalent material, the deflection equation of the supporting edge of the honeycomb structure under the force is established to calculated the equivalent stress and strain. Then, the equivalent elastic modulus and Poisson's ratio are obtained [16, 17].

For a regular hexagonal honeycomb, $t/l < <1$, θ is 60°, and the above formula can be approximately expressed as

$$E_x = E_y = \frac{4}{\sqrt{3}}\left(\frac{t}{l}\right)^3 E_0, \tag{4}$$

$$G_{xy} = \frac{1}{\sqrt{3}}\left(\frac{t}{l}\right)^3 E_0, \tag{5}$$

$$\nu = \nu_0, \tag{6}$$

where E_x is the equivalent elastic modulus of honeycomb plate core in the x direction, E_y is the equivalent elastic modulus of honeycomb plate core in the y direction, E_0 is the elastic modulus of honeycomb plate material, G_{xy} is the equivalent shear modulus of honeycomb plate core, ν is the equivalent Poisson ratio of honeycomb plate, ν_0 is the Poisson ratio of honeycomb plate material, l is the side length of the regular hexagon, and t is the thickness of the aluminum foil.

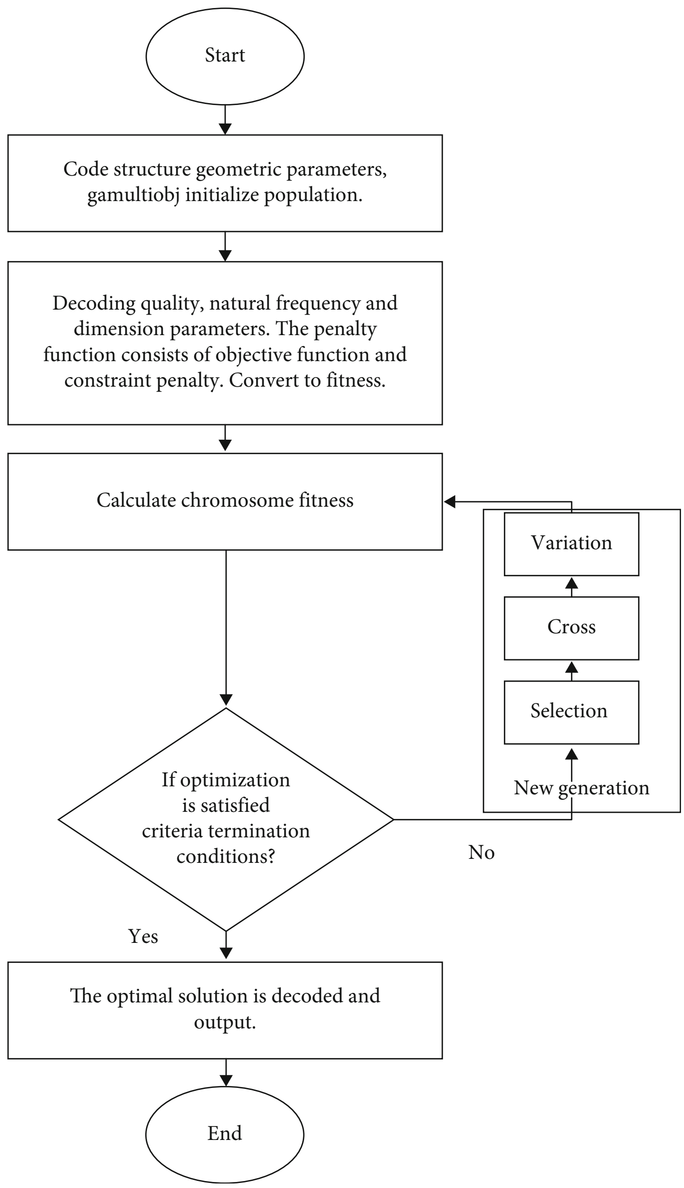


Figure 4: Genetic algorithm programming algorithm flow chart.

2.2. Equivalent Density. At present, the cell of the honeycomb core is usually a regular hexagon, as shown in Figures 2–4. The equivalent density can be obtained from the equal mass before and after the equivalent. And θ is the angle between the hypotenuse and the normal of the transverse edge; so, the equivalent density of the honeycomb core substrate ρ is

$$\rho = \rho_0 \frac{2t}{l \cos \theta (1 + \sin \theta)}, \tag{7}$$

when θ is 60°,and the density is simplified to $\rho = \rho_0 (8t/3\sqrt{3}l)$.

Based on the vibration theory of two-dimensional model of honeycomb sandwich thin plate, the equation of the system frequency of honeycomb sandwich plate and the structure parameters of honeycomb core is established according to the relationship between the equivalent bending stiffness and equivalent density of honeycomb sandwich plate and the frequency of honeycomb sandwich plate.

$$\left| K - M\lambda^2 \right| = 0 \tag{8}$$

where λ the is system angular frequency, $K = D[k_{ij}]$, $M = \rho h [m_{ij}]$, and D and ρ are separately equivalent bending stiffness and equivalent density.

The matrices $[k_{ij}]$ and $[m_{ij}]$ are only related to the in-plate dimension parameters (the length and width of the rectangular honeycomb plate) and Poisson's ratio, instead of the design variables in the honeycomb sandwich structure. Therefore, $[k_{ij}]$ and $[m_{ij}]$ can be regarded as constants.

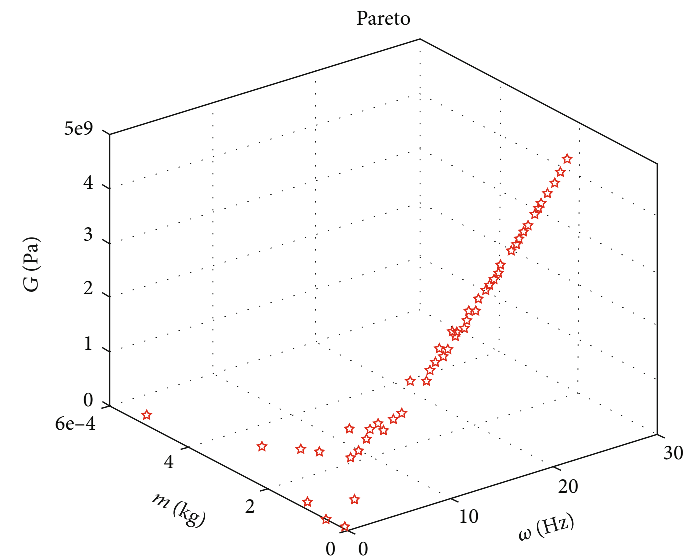


Figure 5: Iteration process of optimization objectives.

According to the matrix operation theory, the natural frequency ω is only related to the coefficients D, ρ, and h of the matrix. Therefore,

$$\omega = \frac{\lambda}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{D}{\rho h}}. \tag{9}$$

3. Dynamic Model of Honeycomb Sandwich Plate Structure

In actual engineering, the purpose of using honeycomb structure materials is to reduce weight, save materials, and ensure the performance of the structure. Specifically, the honeycomb plate bears most of the load in sandwich plane; so, the basic design idea of the honeycomb structure is to obtain as higher bending stiffness as possible and improve the stability of the structure. The design criteria are as follows [18]:

(1) The honeycomb structure plate must have sufficient bending stiffness to avoid damage due to excessive deflection of the entire structure

(2) When ensuring sufficient bending stiffness, the maximum bending strength that the structure can withstand should also be considered

(3) Improve the critical buckling load that the honeycomb structure plate can withstand, that is, improve the stability of the sandwich structure

(4) The weight of the structure should be the lightest on the premise that the honeycomb sandwich structure has better mechanical properties and damping performance

According to the structural design criteria, this paper analyzes the structure from the aspects of reducing the structure quality, improving the bending stiffness, bending strength, and other mechanical properties. Advanced optimization design method is adopted to determine the best configuration of various properties. In this paper, the objective function to be achieved is a multiobjective optimization problem. The objectives are independent physical quantities. The multiobjective genetic algorithm can decouple the influencing factors of the objective function, avoid conflicts, and merge each other into the optimal solution of the global system. Generally, multiobjective planning problems can actually be modeled as the problem of finding Pareto's optimal solution. In the multiple objective case, there does not necessarily exist a solution that is best with respect to all objectives because of incommensurability and conflict among objectives. There usually exists a set of solutions: nondominated solutions or Pareto optimal solutions, for the multiple objective case which cannot simply be compared with each other. At least one target gets better without making any target worse off.

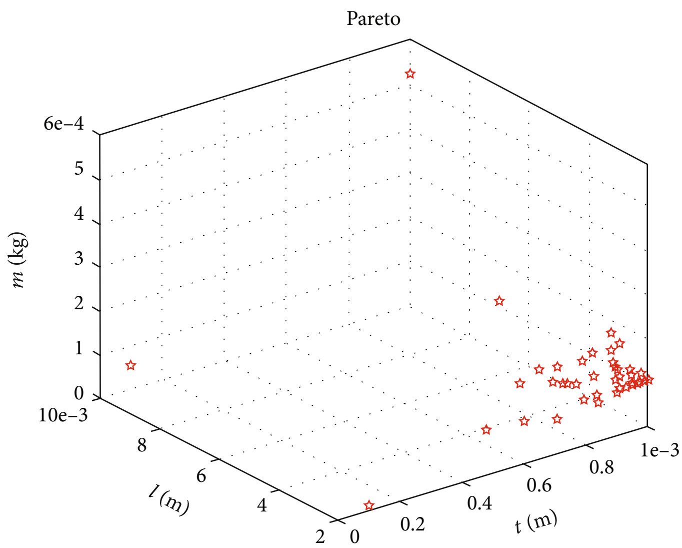
The optimal design of periodic honeycomb plate is based on the unit cell structure, which is the typical embodiment. The unit cell is the basic unit of periodic honeycomb structure, and its overall performance is reproducible and superimposed [19, 20].

The optimized mathematical model of the unit cell of periodic honeycomb plate is as follows:

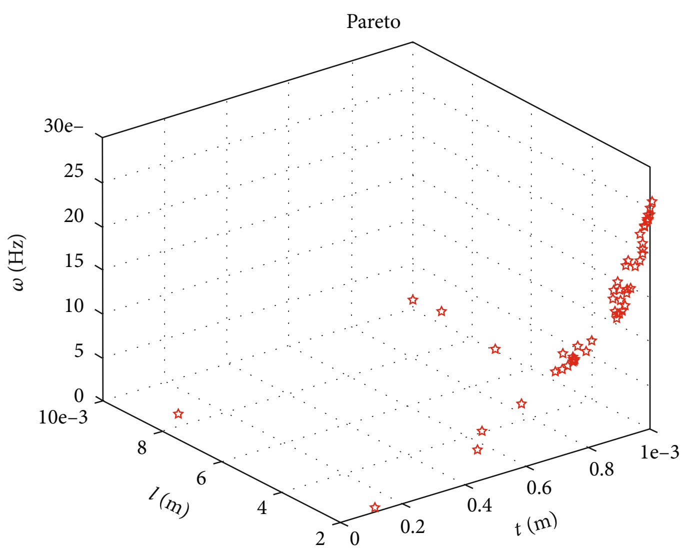
$$\begin{gathered} \text{Find}: X = (x_i), \\ \min\ f(x) = [f_1(x), f_2(x) \cdots, f_{\text{n}}(x)]^{\text{T}}, \\ s.t.: \begin{matrix} x \in X, \\ X \in R^m, \end{matrix} \end{gathered} \tag{10}$$

where $X = (x_i)$ is design variables, and R^m is matrix of parameter ranges.

When the solution x_1 cannot be the optimal value of all $f(x)$, but there is no better solution than x_1, then x_1 is called

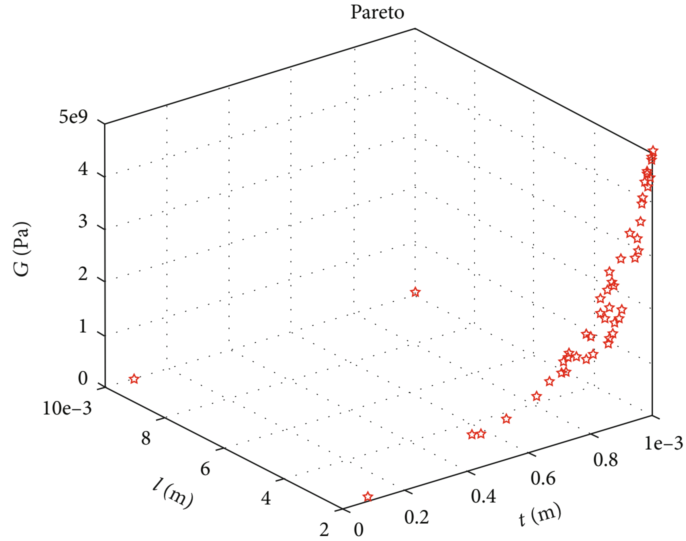


(a)



(b)

Figure 6: Continued.



(c)

Figure 6: The relationships between design variables and objectives functions. (a) The relationship between design variables (t, l) and objective mass (m). (b) The relationship between design variables (t, l) and objective natural frequency (ω). (c) The relationship between design variables (t, l) and objective shear modulus (G).

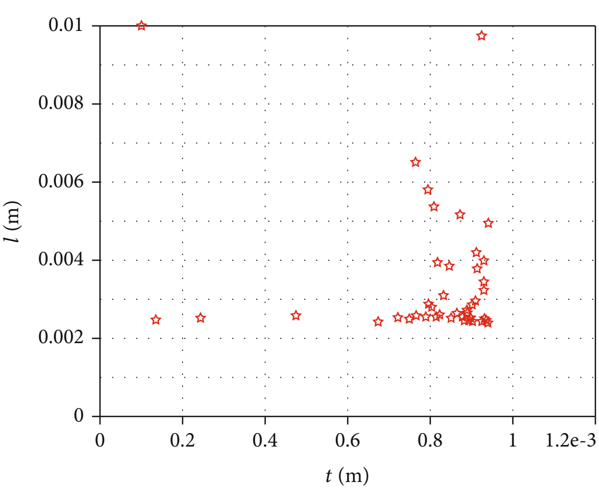


Figure 7: Convergence process of design variables.

the Pareto optimal solution of the multi-objective optimization model.

The genetic algorithm is applied to solve Pareto optimal solution. Each subobjective function $f_i(x)$ $(i = 1, 2, 3 \cdots n)$ is assigned a weight w_i $(i = 1, 2, 3 \cdots, n)$. The linearly weighted sum of each objective function is used as the evaluation function; so, the multiobjective optimization problem is transformed into a single-objective optimization problem, which is solved by genetic algorithm. The optimized program flow is shown in Figure 4.

The genetic algorithm is an adaptive global optimization probabilistic search algorithm formed by simulating the genetic and evolutionary process of organisms in the natural environment. It directly operates on structural objects. Probabilistic methods are used to automatically guide and obtain the optimized search space and adaptively adjust the objective function and fitness function in search direction. The space parameters that represent certain problems are replaced by the populations. The constituent individuals in each population are arranged as the genetic coding space. The chromosome is the main carrier of genetic material. The fitness function is used as the basis for evaluating the population of individuals. The offspring individuals obtained in iterations including selection, crossover, and mutation are always derived from their parent individuals. With the iterative process, the individual fitness gradually improves, and finally, optimal target will be found in the search range.

4. Optimization Design Algorithm of Honeycomb Sandwich Plate

In the multiobjective optimization genetic algorithm of honeycomb plate unit cell structure, the objective functions are the minimum mass of the structure, the stability of hexagonal cell unit, and the maximum bending stiffness and shearing stiffness. The first objective function is the minimum mass of the structure m, which is obtained by multiplying the equivalent density and volume of the structure. The second objective is the maximum stability of hexagonal cell unit, which is mainly reflected in the maximum value of the first-order fundamental frequency ω_1 in the natural frequency of the structure. It can be calculated through stiffness and mass of hexagonal cell which is basic unit of honeycomb sandwich plate. The third kind of objective, maximum stiffness E_x and G_{xy}, is represented by elastic modulus and shear modulus, which are associated with the side length of the regular hexagon l and the thickness of the regular hexagon t. From equation (4), it is easy to know that shear modulus is a quarter of elastic modulus. This paper mainly analyzes the iterative solution of shear modulus. And elastic modulus and shear modulus have the same features and the trends.

The design variables are as follows: the regular hexagon unit cell thickness t, the initial value is 0.0015 m, and the thickness range is [0.0001 0.001] m; the side length of the regular hexagon l, whose initial values is 0.005 m, and the side length adjustment range is [0.002 0.01] m. The constraints are as follows: t is smaller than l, and t is less than a half of l.

Take aluminum alloy honeycomb plate as an example, the elastic modulus of aluminum honeycomb plate E_0 is $7.2 \times 10^{10} \mathrm{N/m^2}$, the Poisson ratio of aluminum honeycomb plate ν_0 is 0.33, and the density of the of aluminum honeycomb core substrate ρ is $2.83 \times 10^3 \mathrm{kg/m^2}$.There are commonly various models of the height H between plates of two sides. This article takes 10 mm as an example.

The optimized design is calculated, and the good global optimal solution is searched and solved. Finally, the optimized values of design variables are obtained.

5. Optimization Results

After the objective function qualities are iterated, the multiobjective genetic algorithm (MOGA) begins to take effect. Thus, the objective function continuously modifies parameters iteration speed and the parameters optimization process. The noninferior Pareto solution set of the multiobjective genetic algorithm finally converges to point with the most frequent numerical occurrences. When the designed optimization algorithm is run multiple times, although the iteration processes are various, the optimization iterations and optimal results are the same. The Pareto solution found by the multiobjective optimization algorithm is shown in Figure 5.

The relationships between design variables and objectives functions in the iteration process are shown in Figure 6.

The iteration process of design variables in optimization algorithm is shown in Figure 7.

From the numerical analysis by the genetic algorithm, the structure optimization of honeycomb core cell is obtained. The structural parameters are optimized, and the results are as follows:

The regular hexagon unit cell thickness t is 0.00095 m, and the side length of the regular hexagon l is 0.0024 m; thus, the mass of the structure m is 0.12 g, the first natural frequency ω_1 is 15.7 Hz, the shear modulus G is 2.5 GPa, and the elastic modulus E is10.3 GPa. Compare the initial values, the mass of the structure m is reduced 69.2%, the first natural frequency ω_1 is changed from initial 15.7 to final 11.4, and the shear modulus G and the elastic modulus E are both nearly doubled of initial values. From the results, it is clearly that the most important objective function, mass of honeycomb core cell, is significantly reduced. Although the natural frequency has not been improved, it still remains at the same order of magnitude. Both the elastic modulus and the shear modulus are significantly increased.

The multiobjective optimization based on the genetic algorithm can deal with the problems that the objective functions are contradictory. That is to say, improving a certain objective function requires to beat the cost of reducing of another objective function. Such a solution by multiobjective genetic algorithm optimization on is called a noninferior solution, also known as Pareto solution.

6. Conclusion

Taking the structure of periodic honeycomb plate core cell as the research object, this paper derives the structural optimization by the multiobjective genetic optimization algorithm. While the overall and local dynamic fundamental frequencies of the system meet the established requirements, the structure optimization design is carried out with the lightest mass, good stability, and high stiffness as the optimization goal. Multiobjective optimization based on the genetic algorithm provides a feasible method to decouple the complex system with multi objectives and multi variable.

Through the method of adjusting the structural parameters within constraints, the mass of the structure could be reduced 69%, and both shear modulus and the elastic modulus are increased clearly, all of which are under the condition of unchanged structure stability. Geometric variables are trained by genetic optimization algorithm, and Pareto solution of optimal form for single cell frame structure is obtained to achieve multiobjective optimization. In the optimization, the optimal values found are all global optimal values within the range that satisfies the constraints, rather than local optimal values, and it also has a high search accuracy.

The optimization design strategy adopted in this paper provides an effective method for improving the system structure, which can reduce the amount of material cost and reduce the investment to a certain extent. It has practical significance in engineering design.

Data Availability

No data were used to support this study.

Conflicts of Interest

There is no potential conflict of interest in this study.

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