1. Introduction

The compliant mechanism is the mechanical structure that transfers movement and energy by elastic deformation of material [1]. The compliant mechanism has the advantages of no friction, no lubrication, no crawling movement, and small design space. Therefore, the compliant mechanism is widely used in precision positioning [2, 3], micromanipulators [4], microscopes [5], robots [6], vibration detection needles [7], and other high-precision fields.

The flexure hinge is the key component of the compliant mechanism, and its mechanical characteristic is related to its structure closely. Notch flexure hinge is the most common type of flexure hinges. There are many types of notch flexure hinges: conic section notch [8, 9], exponential-sine notch [10], double arc notch [11], power function notch [12], segmented curve notch [13], and other types of notch curves [14, 15]. Notch flexure hinge is hard to obtain high motion accuracy and large motion range at the same time. Therefore, many flexure hinges with a complex structure such as triple-cross-spring flexure hinges [16], cartwheel flexure hinge [17], and butterfly flexure hinges [18] have been designed and analyzed. The more extensive the application scenarios of flexure hinges become, the higher the requirements for the performance of flexure hinges such as range and damping are. These high performances all rely on more and more complex structures. However, traditional technology cannot manufacture flexure hinges with special complex structures. Additive manufacturing (AM) is an emerging manufacturing process that can manufacture complex structures (such as the structure obtained by topology optimization [19]). Many researchers have introduced AM technology into the manufacturing of compliant mechanisms. Merriam et al. [20] proposed a flexure mechanism based on a truss-like lattice, which significantly improved the working stroke. Chen et al. [21] studied comb-shaped flexible hinges. Adding a comb-shaped structure to the straight circular flexure hinge can increase the motion damping and improve the dynamic characteristics.

Many researchers have conducted research on the material composed of the truss lattice structure. Wang et al. [22] researched the mechanical behavior of the pyramidal lattice truss core Sandwich panels. Zhang et al. [23] proposed a method of manufacturing carbon fiber reinforced polymer.
(CFRP) tetrahedral lattice truss core Sandwich structure by thermal expansion silicon rubber mold, and the mechanical properties of CFRP tetrahedral lattice truss core Sandwich structures were investigated. Gross et al. [24] investigated the response of four topologically distinct truss lattice architectures to the inclusion of defects in order to elucidate how defects influence the elastic properties of these materials. Ye et al. [25] designed and manufactured pyramid lattice truss structures and researched the mechanical properties and energy absorption of the pyramidal lattice truss structures. However, these studies only focus on the strength performance and vibration performance of materials, and there are few studies on the elastic deformation characteristics of truss lattice structures. Merriam et al. [26] introduced a flexure type called lattice flexures and evaluates some of their fundamental properties. But the research in this paper is limited to the compliance on two degrees of freedom.

A genetic algorithm is a widely used optimization algorithm. Many researchers have applied genetic algorithms to the structural optimization of compliant mechanisms. Parsons et al. [27] explored the use of a random guided search method for multiobjective optimization of compliant mechanisms through genetic programming techniques. Sharma et al. [28] developed a domain-specific initial population strategy that generates geometrically feasible structures for path generating compliant mechanisms. Chau et al. [29] developed an efficient hybrid optimization approach of central composite design, finite element method, artificial neural network, and multiobjective genetic algorithm for a linear compliant mechanism of nanoindentation tester. Whether the genetic algorithm can be used in the optimization of lattice structure needs further research.

The structure of lattice structure is complex, and the influence of various structural parameters on the overall mechanical properties is different. Therefore, exploring the impact of various structural parameters on the overall performance is important for the research of the characteristics of additive manufacturing structures. Moreover, proposing a structural optimization method for the additive manufacturing structure is very important to the design of the additive manufacturing structure. In this paper, the flexure hinge based on X-lattice structure is researched, and a structure optimization method based on a genetic algorithm is proposed. The content of Section 2 is mainly about the compliance modeling of the flexure hinge. The content of Section 3 is mainly about further analysis of the flexure hinge based on the X-lattice structure. The content of Section 4 is mainly about a structure optimization method based on a genetic algorithm, and this method is applied to a flexure hinge based on the X-lattice structure.

2. Compliance Model

Structures of the traditional beam flexure hinge and the flexure hinge based on X-lattice structure are shown in Figure 1, where Figure 1(a) is a structure of the traditional beam flexure hinge, Figure 1(b) is a structure of the single X-lattice, Figure 1(c) is a structure of the beam flexure hinge consisting of 4 X-lattices (single row: 4 × 1), and Figure 1(d) is a structure of the beam flexure hinge consisting of 8 X-lattices (double row: 4 × 2). In this section, the beam model in the finite element analysis is used to obtain the six-degree-of-freedom (DOF) compliance matrix of the single X-lattice structure. Then, the six-DOF compliance matrix of the single X-lattice structure beam flexure hinge consisting of several X-lattices is obtained in the same way.

2.1. Compliance Model of Single X-Lattice. Definition of the structural parameters of the X-lattice structure is shown in Figure 2. The thickness is \( h \); the width of the support beam on the boundary is \( t_1 \); the width of the beam of X-lattice is \( t_2 \); the length of the X-lattice is \( l_1 \); the width of the X-lattice is \( l_2 \); the length of the beam of X-lattice is \( l_3 \); the angle between the support beam on the boundary and the beam of X-lattice is \( \alpha \). The relationship between structural parameters is shown as follows:

\[
\begin{align*}
\cos \alpha &= \frac{l_1(1-(1/\sin \alpha))}{2l_1+t_2(1+(1/\tan \alpha))}, \\
\sin \alpha &= \frac{l_2}{2l_1+t_2(1+(1/\tan \alpha))}.
\end{align*}
\]

The structure in Figure 2 is separated as shown in Figure 3, and the node numbers and unit numbers are shown in Figure 3. The blue nodes 1 and 2 among 5 nodes are located at the fixed end. Beam elements \( \varnothing, \varnothing, \varnothing, \) and \( \varnothing \) are beam elements forming the X-lattice structure, and \( \varnothing \) and \( \varnothing \) are the support beam elements on the boundary. Point \( P \) where the load is applied to the X-lattice structure is the midpoint of the connecting line between nodes \( \varnothing \) and \( \varnothing \). Definition of the coordinate system and the definition of loads applied externally are shown in Figure 3.

The transformation relationship between the local coordinate system and the global coordinate system of the beam element is shown in Figure 4. There are two nodes on two ends of the beam element. The displacement matrix and load matrix of the end node in the local coordinate system are as follows:

\[
\begin{align*}
q &= \begin{bmatrix} \delta x_{i1} & \delta y_{i1} & \delta z_{i1} & \theta x_{i1} & \theta y_{i1} & \theta z_{i1} & \delta x_{i2} & \delta y_{i2} & \delta z_{i2} & \theta x_{i2} & \theta y_{i2} & \theta z_{i2} \end{bmatrix}^T, \\
P &= \begin{bmatrix} Fx_{i1} & Fy_{i1} & Fz_{i1} & Mx_{i1} & My_{i1} & Mz_{i1} & Fx_{i2} & Fy_{i2} & Fz_{i2} & Mx_{i2} & My_{i2} & Mz_{i2} \end{bmatrix}^T.
\end{align*}
\]
The displacement matrix in the global coordinate system is as follows:

\[
\mathbf{q} = \begin{bmatrix} \delta x_1 \\ \delta y_1 \\ \delta z_1 \\ \delta x_{11} \\ \delta y_{11} \\ \delta z_{11} \\ \delta x_{12} \\ \delta y_{12} \\ \delta z_{12} \end{bmatrix}.
\]  

(3)

The relationship between matrixes (displacement matrix and load matrix) in the global coordinate system and the local coordinate system can be expressed as

\[
\mathbf{q} = \mathbf{T}^T \cdot \tilde{\mathbf{q}},
\]

\[
\mathbf{P} = \mathbf{T}^{TR} \cdot \mathbf{P},
\]  

(4)
and $j$ is the number of the beam element ($j = 1, 2, 3, 4, 5, 6$). The transformation matrix of coordinate system $T'$ is [30]

$$
T^{j}_{(12 \times 12)} = \begin{bmatrix}
\lambda^j & 0 & 0 & 0 \\
0 & \lambda^j & 0 & 0 \\
0 & 0 & \lambda^j & 0 \\
0 & 0 & 0 & \lambda^j \\
\end{bmatrix},
$$

where

$$
\lambda^j_{(3 \times 3)} = \begin{bmatrix}
\cos(j x', x) & \cos(j y', y) & \cos(j z', z) \\
\cos(j x', x) & \cos(j y', y) & \cos(j z', z) \\
\cos(j z', x) & \cos(j z', y) & \cos(j z', z) \\
\end{bmatrix},
$$

In equation (6), $\cos(x', x)$, $\ldots$, $\cos(z', z)$ represent the direction cosine of the local coordinate axis ($x', y', z'$) of the beam numbered $j$ to the global coordinate axis ($x$, $y$, $z$), respectively.

The elements in the coordinate transformation matrix of each beam element of the X-lattice structure in Figure 2 are shown in Table 1.

The stiffness equation of the beam element in the global coordinate system is

$$
\overline{R}^{j}_{(12 \times 12)} \cdot \overline{q} = \overline{F},
$$

where

$$
\overline{R}^{j}_{(12 \times 12)} = T^{j}_{(12 \times 12)} \cdot K^{j}_{(12 \times 12)} \cdot T^{j}_{(12 \times 12)},
$$

$$
K^{j}_{(12 \times 12)} = \begin{bmatrix}
\frac{EA}{l} & 0 & 0 & 0 & 0 & 0 & \frac{-EA}{l} & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_z}{l^3} & 0 & 0 & 0 & 6EI_z & 0 & \frac{-12EI_z}{l^3} & 0 & 0 & 0 & \frac{6EI_z}{l^3} \\
0 & 0 & \frac{12EI_y}{l^3} & 0 & 6EI_y & 0 & 0 & 0 & \frac{-12EI_y}{l^3} & 0 & \frac{6EI_y}{l^3} & 0 \\
0 & 0 & 0 & \frac{GJ}{l} & 0 & 0 & 0 & 0 & 0 & \frac{-GJ}{l} & 0 & 0 \\
0 & 0 & \frac{6EI_y}{l^3} & 0 & \frac{4EI_z}{l} & 0 & 0 & 0 & \frac{-6EI_z}{l^3} & 0 & \frac{2EI_z}{l} & 0 \\
0 & 6EI_z & 0 & 0 & 0 & \frac{4EI_z}{l} & 0 & \frac{-6EI_z}{l^3} & 0 & 0 & 0 & \frac{2EI_z}{l} \\
\frac{EA}{l} & 0 & 0 & 0 & 0 & 0 & \frac{-EA}{l} & 0 & 0 & 0 & 0 \\
0 & \frac{-12EI_z}{l^3} & 0 & 0 & 0 & \frac{-6EI_z}{l^3} & 0 & \frac{12EI_z}{l^3} & 0 & 0 & 0 & \frac{-6EI_z}{l^3} \\
0 & 0 & \frac{-12EI_y}{l^3} & 0 & \frac{6EI_y}{l^3} & 0 & 0 & 0 & \frac{-12EI_y}{l^3} & 0 & \frac{6EI_y}{l^3} & 0 \\
0 & 0 & 0 & \frac{-GJ}{l} & 0 & 0 & 0 & 0 & 0 & \frac{GJ}{l} & 0 & 0 \\
0 & 0 & \frac{6EI_y}{l^3} & 0 & \frac{-2EI_z}{l} & 0 & 0 & 0 & \frac{6EI_z}{l^3} & 0 & \frac{-2EI_z}{l} & 0 \\
0 & 6EI_z & 0 & 0 & 0 & \frac{-2EI_z}{l} & 0 & \frac{6EI_z}{l^3} & 0 & 0 & 0 & \frac{-4EI_z}{l} \\
\end{bmatrix},
$$

Complexity
In the above formulas, $A$ is the cross-sectional area of the beam; $I$ is the length of the beam; $E$ is Young's modulus of the beam material; $G$ is the shear modulus; $\alpha$ is the torsional moment of inertia of the cross section; $I_y$ is the inertia moment around the $y$-axis; $I_z$ is the inertia moment around the $z$-axis; and $n$ is the node number.

The stiffness matrix can be simplified as

$$K^l_{ij} = \begin{bmatrix} K_{11}^l & K_{12}^l \\ K_{21}^l & K_{22}^l \end{bmatrix},$$ \hspace{1cm} (10)

where $K_{ij}^l$ is the element of the $i$-th row and $j$-th column of the stiffness matrix. The total displacement matrix of the X-lattice structure in Figure 3 is expressed as

$$q_{total}^{\text{(1×30)}} = [q_{total1}^{\text{(1×30)}} \ q_{total2}^{\text{(1×30)}} \ q_{total3}^{\text{(1×30)}} \ q_{total4}^{\text{(1×30)}} \ q_{total5}^{\text{(1×30)}}],$$ \hspace{1cm} (11)

where

$$q_{total}^{\text{(1×6)}} = [\delta x_n \ \delta y_n \ \delta z_n \ \theta x_n \ \theta y_n \ \theta z_n],$$ \hspace{1cm} (12)

where $n$ is the node number ($n = 1, 2, 3, 4, 5$). The total load matrix of the X-lattice structure is

$$P_{total} = \begin{bmatrix} P_{total1}^{\text{(1×6)}} & P_{total2}^{\text{(1×6)}} & P_{total3}^{\text{(1×6)}} & P_{total4}^{\text{(1×6)}} & P_{total5}^{\text{(1×6)}} \end{bmatrix},$$ \hspace{1cm} (13)

where

$$P_{total_n} = [Fx_n \ Fy_n \ Fz_n \ Mx_n \ My_n \ Mz_n].$$ \hspace{1cm} (14)

According to formula (9) and the structure stiffness matrix assembly rule in the finite element analysis [1], the stiffness matrix of the X-lattice structure can be expressed as

$$K_{total}^{\text{(30×30)}} = \begin{bmatrix} K_{11}^1 + K_{11}^2 & K_{21}^1 + K_{21}^2 & K_{31}^1 + K_{31}^2 & K_{41}^1 + K_{41}^2 & K_{51}^1 + K_{51}^2 \\ K_{11}^2 & K_{22}^2 & K_{32}^2 & K_{42}^2 & K_{52}^2 \\ K_{12}^3 & K_{23}^3 & K_{32}^3 & K_{43}^3 & K_{53}^3 \\ 0 & 0 & 0 & 0 & 0 \\ K_{13}^4 & K_{24}^4 & K_{34}^4 & K_{44}^4 & K_{54}^4 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$ \hspace{1cm} (15)

It can be seen from Figure 3 that the boundary condition of stiffness equation (7) is $q_{total1} = q_{total2} = 0$.

Loads on six-DOF are applied on point $P$, and then, the displacement of node 4 and node 5 is calculated. The
compliance of the X-lattice structure in the direction of six-DOF can be obtained as follows:

\[
\begin{align*}
\kappa_{Y_{\text{single}}} &= \frac{\delta_{y4} + \delta_{y5}}{Fy}, \\
\kappa_{X_{\text{single}}} &= \frac{\delta_{x4} + \delta_{x5}}{Fx}, \\
\kappa_{Z_{\text{single}}} &= \frac{\delta_{z4} + \delta_{z5}}{Fz}, \\
\kappa_{RX_{\text{single}}} &= \frac{\gamma_{y4} - \gamma_{y5}}{Mx(l_2 + t_1)}, \\
\kappa_{RY_{\text{single}}} &= \frac{\gamma_{x4} - \gamma_{x5}}{My(l_2 + t_1)}, \\
\kappa_{RZ_{\text{single}}} &= \frac{\gamma_{y4} + \gamma_{y5}}{Mz \cdot l_4^2}.
\end{align*}
\]  

(16)

2.2. Compliance Model of Flexure Hinge Based on X-Lattice. The structures of beam flexure hinge based on X-lattice structure and nodes and elements are shown in Figure 5 and Figure 6. In Figure 6, \(q - 1\) is the number of X-lattice structural units in the \(z\)-direction, and \(p - 1\) is the number of X-lattice structural units in the \(x\)-direction. The definition of structure parameters of the beam flexure hinge based on X-lattice structure is the same as that of a single X-lattice structure. Node numbers and beam element numbers are shown in Figure 7. The numbers without square brackets are node numbers, and those with square brackets are beam element numbers.

According to formulas (5)–(9) and the structure stiffness matrix assembly rule in the finite element analysis [30], the stiffness matrix of the beam flexure hinge based on X-lattice can be obtained. It can be seen from Figure 6 that the boundary condition of the stiffness equation is \(q_{\text{total}_1} = q_{\text{total}_2} = \ldots = q_{\text{total}_q} = 0\). Loads on six-DOF are applied on point \(P\), and the displacement of all nodes can be calculated. The compliance of the X-lattice structure can be obtained and it can be expressed as

\[
\begin{align*}
\kappa_Y_{\text{total}} &= \frac{\sum_{i=1}^{q_{\text{total}_1}} \delta_{yi}}{Fy}, \\
\kappa_X_{\text{total}} &= \frac{\sum_{i=1}^{q_{\text{total}_2}} \delta_{xi}}{Fx}, \\
\kappa_Z_{\text{total}} &= \frac{\sum_{i=1}^{q_{\text{total}_3}} \delta_{zi}}{Fz}, \\
\kappa_{RX_{\text{total}}} &= \frac{\sum_{i=1}^{q_{\text{total}_4}} \delta_{x(i-1)} - \delta_{x(i)}}{Mx \cdot l_3}, \\
\kappa_{RY_{\text{total}}} &= \frac{\sum_{i=1}^{q_{\text{total}_5}} \delta_{y(i-1)} - \delta_{y(i)}}{My \cdot l_3}, \\
\kappa_{RZ_{\text{total}}} &= \frac{\sum_{i=1}^{q_{\text{total}_6}} \delta_{z(i-1)} - \delta_{z(i)}}{Mz \cdot l_4}.
\end{align*}
\]  

(17)

3. Performance Analysis and Discussion

The compliance performance of the beam flexure hinge based on the X-lattice structure is analyzed in this section. There are three performance items: compliance, compliance ratio between working direction and nonworking direction, and the performance comparison with the traditional beam flexure hinge. The compliance of each DOF can be used to express the ability of deformation in each direction. The compliance ratio can be used to reflect the stability of the flexure hinge when it deforms in the working direction. Performance comparison with traditional beam flexure hinge can be used to evaluate the performance improvement of the X-lattice structure to the flexible hinge quantitatively.

3.1. Compliance. The influence of various structural parameters on the compliance of the flexure hinge is researched. There are specific constraints as follows:

(i) \(p = 3, q = 3\)

(ii) The length of the flexure hinge in the \(x\)-direction \(l_4 = 40\) mm

(iii) The length of the flexure hinge in the \(z\)-direction is \(l_5 = 20\) mm

(iv) Thickness of flexure hinge \(h = 1.5\) mm
(v) The range of the width of the beam element of X-lattice $t_2$: [0.5 mm, 5 mm]

(vi) The range of angle between X-lattice beam elements $\alpha$: [$\pi/6$, $\pi/2$]

The material of the flexure hinge is spring steel (60Si2Mn), Young’s modulus is $E = 206$ GPa, and Poisson’s ratio is $\nu = 0.29$.

The influence of $\alpha$ and $t_2$ on the compliance ratio of flexure hinge based on the X-lattice structure is shown in Figure 9.

It can be seen from Figure 9 that $c_y/c_x, c_y/c_z$, and $c_y/c_\theta$ all increase as $\alpha$ increases and decrease as $t_2$ increases. $c_y/c_\theta$ increases with the increase of $\alpha$ and $t_2$. The change of $c_y/c_\theta$ with $\alpha$ and $t_2$ has no obvious rule.

3.3. Performance Comparison with Traditional Beam Flexure Hinge

In order to research the influence of the X-lattice structure on the performance of the beam flexure hinge, two types of hinges with the same external dimensions are researched. Structural parameters of two types of flexure hinges are shown in Table 2.

The finite element simulation method based on the Ansys workbench is used to explore the compliance of flexure hinges. The Mesh model of flexure hinges is shown in Figure 10. The material is set as spring steel (60Si2Mn), the Young modulus $E = 206$ GPa, and Poisson’s ratio $\nu = 0.29$. Simulation results are shown in Tables 3 and 4.

It can be clearly seen from Table 4 that the X-lattice structure significantly improves the compliance ratio of the flexure hinge under the same external dimensions. The improvement of compliance ratio represents that the flexure hinge based on the X-lattice structure has higher stability than the traditional beam flexure hinge when deformation is produced.

4. Structure Optimization of Flexure Hinge

In high-precision engineering fields, the compliance of flexure hinges in the working direction usually should be large, and the compliance of flexure hinges in nonworking directions should be small. In Section 3, it is obvious that the influence of structural parameters on the compliance characteristics of flexure hinge based on X-lattice structure is different. It is difficult to obtain the flexure hinge structure

Figure 5: The structure of beam flexure hinge based on X-lattice.

Figure 6: Definition of the coordinate system of the flexure hinge based on X-lattice.
with good performance that meets the engineering demand through ordinary methods. The genetic algorithm transforms the problem-solving process into a process similar to the crossover and mutation of chromosomal genes in biological evolution by means of mathematics and computer simulation operations. Compared with some conventional optimization algorithms, optimization results can usually be obtained faster by a genetic algorithm. Moreover, a specific mathematical model is not required in a genetic algorithm. Therefore, the application of the genetic algorithm is extensive. In this section, a multiobjective structural optimization method based on a genetic algorithm is proposed in this section. The flexure hinge with the best performance under the specified design constraints can be obtained through this method.

4.1. Optimization Method. A genetic algorithm is an intelligent optimization algorithm that simulates the genetic inheritance of biological genes. The task of the genetic algorithm is to impose certain operations on the individuals of the group according to their environmental fitness, and the evolution process of survival of the fittest can be realized. The genetic algorithm can optimize the solution of the problem generation after generation and approach the optimal solution from the perspective of optimization search. The optimization process of the genetic algorithm is shown in Figure 11. The specific steps are as follows:

1. A population as the first generation solution of the problem is generated randomly
2. A suitable coding scheme is used to encode individuals in the population. Common coding schemes such as floating-point number coding or binary coding can be used.
3. The value of the optimization function is used as the fitness of the individual, and the fitness of each individual in the population is calculated.
4. According to the level of fitness, the parent and the mother to participate in reproduction are chosen. The principle of selection is that the higher the fitness, the more likely to be selected.
5. Perform genetic operation is applied on the selected father and mother; that is, the genes of the father and mother are copied, and crossing, mutation, or other operators are used to produce offspring.
6. According to a certain criterion, whether to continue the algorithm is judged.

4.2. Optimization Case. In order to show the effectiveness of the optimization method, the above optimization method in Section 4.1 is used to obtain the flexure hinge based on the X-lattice structure with the best comprehensive compliance characteristics.
The comprehensive flexibility ratio of the flexure hinge can be used to reflect the stability of the flexure hinge when it deforms in the working direction. The comprehensive flexibility ratio of the flexure hinge is structurally optimized under the given constraints in this section. The optimization model is

\[
\text{find (Structure)} \quad \text{to maximize} \quad c_{\text{ratio sum}}(t_1, t_2, \alpha, l_1, l_2, l_3) \\
\text{subject to} \quad c_y \geq c \ast \text{size}_{\text{design space}} = \text{size} \ast,
\]
where the definition of $t_1$, $t_2$, $\alpha$, $l_1$, $l_2$, and $l_3$ is the same as before; $c_*$ is the specified minimum value of compliance; size $*$ is the specified design space; $c_{\text{ratio}_\text{sum}}$ is the multiobjective comprehensive compliance ratio of the flexure hinge, and it is the linear weighted sum of the compliance ratio of five nonworking directions. The specific expression is as follows:

$$
c_{\text{ratio}_\text{sum}} = k_1 n_1 \frac{c_y}{c_x} + k_2 n_2 \frac{c_y}{c_z} + k_3 n_3 \frac{c_y}{c_{\theta x}} + k_4 n_4 \frac{c_y}{c_{\theta y}} + k_5 n_5 \frac{c_y}{c_{\theta z}}
$$

It can be seen from the above that the order of magnitude of every compliance ratio value is different, so $n_1$, $n_2$, $n_3$, $n_4$, $n_5$.
and $n_5$ are introduced as normalization parameters. In formula (19), $k_1$, $k_2$, $k_3$, $k_4$, and $k_5$ are the weight of each compliance ratio in the comprehensive compliance ratio:

$$k_1 + k_2 + k_3 + k_4 + k_5 = 1.$$  

\[ (20) \]

4.2.1. Parameter Initialization. First of all, the material is set as spring steel (60Si2Mn), the Young modulus $E = 206$ GPa, and Poisson’s ratio $\nu = 0.29$. The external structural parameters of the flexure hinge are shown in Table 5, and the range of structural parameters provided for optimization is shown in Table 6.

The values of weight and normalization parameters in the objective function are set as shown in Table 7 according to the previous research results and specific engineering applications.

4.2.2. Optimization Result. The structural parameters are optimized according to the steps in Section 4.1. The optimization process of the objective function is shown in Figure 12.

The optimized structural parameters are shown in Table 8, and the structure is shown in Figure 12.

The optimized structure has the highest $c$-ratio under the specified design constraints. The structure has low compliance in each nonworking direction and high compliance in the working direction. The structure has a strong resistance ability to disturbance forces in nonworking directions when deformed, and its motion stability is high.
Figure 11: The optimization process of a genetic algorithm.

Table 5: External structural parameters.

| Parameter | $l_4$ (mm) | $l_5$ (mm) | $h$ (mm) |
|-----------|------------|------------|----------|
| Value     | 80         | 20         | 1.5      |

Table 6: Range of structural parameters provided for optimization.

| Parameter | $t_1$ (mm) | $t_2$ (mm) | $\alpha$ (rad) | $l_1$ (mm) | $l_2$ (mm) | $l_3$ (mm) |
|-----------|------------|------------|----------------|------------|------------|------------|
| Range     | [0,1,5]    | [0,1,5]    | [$\pi/9$, $\pi/2$] | [0, 30]    | [0, 30]    | [0, 30]    |

Table 7: The value of weight and normalization parameters.

| Parameter | $k_1/n_1$ | $k_2/n_2$ | $k_3/n_3$ | $k_4/n_4$ | $k_5/n_5$ |
|-----------|-----------|-----------|-----------|-----------|-----------|
| Value     | $1/(1/600)$ | $1/(1/10)$ | $1/(10^4)$ | $1/(1/10^6)$ | $1/(1/10^6)$ |

Figure 12: The optimization process of a genetic algorithm.
5. Conclusions

The truss model in the finite element method is used to model the 6-DOF compliance of the flexure hinge based on the X-lattice structure. The influence of structural parameters on the compliance and compliance ratio of flexure hinges is analyzed based on this model, and the performance is compared with the traditional beam flexure hinge of the same size. According to the analysis results, it can be seen that the compliance ratio performance of the flexure based on the X-lattice structure is significantly better than that of the traditional beam flexure hinge. Due to the different influence rules of various parameters on flexure hinges, it is difficult to obtain the structure of flexure hinge with a good performance by a common method. In order to design a flexure hinge with good comprehensive performance, this paper proposes an intelligent structure optimization method based on a genetic algorithm. The feasibility of the optimization algorithm is verified by an example.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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