Research on Light-Small Lens Structure Design and Weight Reduction Optimization Based on Neural Network

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ABSTRACT: In order to meet the design requirements of low weight and high specific stiffness for a small space camera lens assembly, based on the compact coaxial four-mirror optical system, a dynamic optimization design concept is proposed firstly, and then the initial lightweight design of lens structure is realized in an integrated assembly form. And then the BP neural network & genetic algorithm is used to dynamically optimize the lens structure parameters, which reduces the weight of the whole lens while ensuring the high specific stiffness of the lens, and realizes the goal of lens lightening design.

1. INTRODUCTION TO THE RESEARCH

For space load, the reduction of its weight can greatly reduce the launch cost, so there is a weight requirement for the lens assembly of a certain type of small camera. According to the requirements of this model, the weight of the whole lens must be controlled below 1.8 kg, the fundamental frequency must be greater than 180 Hz, and the size of the whole lens should be controlled within the range of φ230 mm x 210 mm. In order to achieve the design goal of miniaturization of lens assembly and meet the requirement of high specific stiffness, this paper proposes a weight reduction idea combining structural design with dynamic optimization. First, the initial lens structure model is designed, and then some size parameters of lens are fine-tuned by dynamic optimization to achieve further weight reduction.

Dynamic optimization design refers to the optimization design problem that includes the dynamic characteristics or dynamic response of the structure in the objective or constraint of the optimization design model. The optimization can realize the weight reduction design and higher stiffness requirement of the structure by changing the size of the parts. The mathematical model is as follows[1]:

Find a set of design variables X=[x1,x2,...,xn]T,Let:

\[ f(x) = \text{min} \]

s.t. \[ g_i(X) \leq 0 \quad (i = 1,2, \ldots, L) \]
\[ q_j(X) \leq 0 \quad (i = 1,2, \ldots, M) \]
\[ u_k(X) \leq 0 \quad (i = 1,2, \ldots, T) \]
\[ x_l^r \leq x_r \leq x_u^r \quad (r = 1, 2, \ldots, N) \]

Where \( G_i(X) \) is a static constraint function;
\( Q_j(X) \) is a dynamic constraint function;
\( U_k(X) \) is another constraint function;
\( x_l^r, x_u^r \) are the lower and upper limits of the design variable \( x_r \), respectively.

The premise of dynamic optimization is that there is a better structural model. So before optimization, this paper integrates all mirrors into the same connector with the design idea of integrated assembly, reduces the number of connecting elements, and achieves weight reduction in structural design. Then, the finite element model of the lens is established, and some sizes suitable for adjusting in the finite element model of the lens are determined as design variables. By changing the sizes of design variables, the weight and fundamental frequency of the lens in different sizes are obtained respectively. With the input and output data of different sizes of design variables and their weights and fundamental frequencies, the BP neural network model is built, trained and tested. When the test results meet the error conditions, the model of the BP neural network is successful. Taking weight as optimization objective and fundamental frequency as constraint function, genetic algorithm is used to optimize the constructed neural network model, and the optimal solution and variable value are obtained. Modify the value of the variable by integer and so on, and the final parameters are brought into the finite element model to verify the weight and fundamental frequency. Finally, a small lens with light weight and high stiffness is obtained.

2. STRUCTURAL DESIGN OF LIGHT-SMALL LENS

The optical designer of the lens chooses the optical system[2,3] as shown in Figure 1 according to the relevant requirements, and adds a folding mirror after the quaternary mirror to fold the optical path to make the volume more compact. From primary mirror to quaternary mirror, the aperture are 200 mm, 80 mm, 100 mm and 28 mm, respectively. According to the figure 1, quaternary mirror can be used as field of view diaphragm to shield stray light. This feature can be used in structural design to shorten the length of the external shade and realize weight loss.

![Figure 1. Optical system](image)

Figure 1. Optical layout. I-Primary mirror. II-Secondary mirror. III-Tertiary mirror. IV-Quaternary mirror

In this paper, a lightweight design method is adopted for the design of mirror. As shown in the Figure 2, taking the secondary mirror as an example, its initial thickness is 10mm and its weight is 92g. Because of its small thickness, considering the lightweight degree and the difficulty of processing comprehensively, lightweight holes are excavated from the back, edge thickness is reduced, instead of processing blind holes on the side[4].

![Figure 2. Design of secondary mirror with lightweight form](image)

Figure 2. Design of secondary mirror with lightweight form

The primary mirror uses the same form to achieve lightweight design. The distance between the top
to the back of the tertiary mirror is small, which makes it inconvenient to design lightweight holes. Therefore, the back edge material is cut accordingly only according to the radian of the mirror. For the quaternary mirror, the aperture and thickness are very small. Considering the difficulty of processing, the lightweight design is not adopted. Through calculation, the lightweight rates of primary, secondary and tertiary mirrors were 73%, 59% and 57%, respectively.

In order to give full play to the advantages of quaternary mirror in eliminating stray light and to realize the weight reduction assembly of mirrors, an integrated extinction and connection element can be designed to suppress stray light more effectively and realize mirror connection. Based on this idea, this paper designs the extinction cylinder as shown in the Figure 3. The relative position of the reflector and the extinction cylinder is marked in the figure (I, II, III, IV Represents the position of the primary mirror to the quaternary mirror, respectively). The light is reflected by the secondary mirror, and it enters the extinction cylinder through the central hole of the quaternary mirror to continue to propagate. By using the aperture function of the extinction cylinder and the mirror, stray light can be suppressed in a compact space. In this way, the lens does not need an external shade, which greatly reduces the weight and volume of the lens.

Figure 3. Sectional view extinction cylinder

For coaxial reflective optical systems, in general, the mirror is connected to the inner shade by three-bar support. However, because the diameter of the inner shade is much larger than that of the secondary mirror, the quaternary mirror and the quaternary mirror, if the mirror is connected by three bars, the bars will be relatively long, which will cause more weight gain of the whole machine. For coaxial reflective optical systems, in general, the mirror is connected to the inner shade by three-bar support. However, because the diameter of the inner shade is much larger than that of the secondary mirror, the quaternary mirror and the quaternary mirror, if the mirror is connected by three rods, the rods will be relatively long, which will cause more weight gain of the whole machine. In order to reduce the weight of connecting elements, this paper makes full use of extinction cylinder as the connecting element of reflector, completes the integration of optical components, realizes the integration of structural forms, better meets the thermal matching of optical elements, greatly reduces the weight of main structure, and meets the development requirements of micro lens. The aperture and thickness of the mirror in this paper are relatively small. The stability of the mirror can be guaranteed by installing the mirror on the wall of the extinction cylinder by gluing. Therefore, the internal diameters of the central opening of the primary and secondary mirrors are respectively connected to the outer diameters of the corresponding positions of the extinction cylinder shown in the figure. The protruding parts of the central hole of the quaternary mirror are glued to the holes at the bottom of the extinction cylinder, and the outer diameters of the quaternary mirror are glued to the inner diameters of the inner hole of the extinction cylinder. At the same time, in the section view shown in Figure 3, the protrusion of the installation position of the primary, secondary and tertiary mirrors in the axial contact with the mirror can limit the displacement of the primary and secondary mirrors in the optical axis direction; the quaternary mirror have small aperture and weight, so this method is not necessary.

For the folding mirror, according to its position in the optical system, it is assembled in the frame and connected to the bottom of the extinction cylinder with three sets of bipod supports. For all the above components, including the inner shade of the lens, the C/Sic material with high specific stiffness is used in this paper, which ensures the thermal matching of the lens structure while realizing the high specific stiffness of the lens.

The lens and the satellite platform are connected by three groups of flexible bipod support. The
form of the support is shown in Figure 4. The support is made of aluminum alloy. When the stress is
transferred from the satellite platform to the lens, the flexible support deforms first, thereby releasing
the stress and ensuring the stability of the main structure of the lens.

![Figure 4. Flexible support connecting lens and satellite platform](image)

After the design of each part is completed, the assembly body is shown as shown in the Figure 5.
After calculation, the lens weight is 1.827 kg and the volume is φ220mm * 190mm. The volume
meets the requirements of the structural design, and the weight ratio is slightly higher than the required
1.8kg, so the weight reduction design needs to be carried out through subsequent optimization.

![Figure 5. Assembly body of lens](image)

3. RESEARCH ON NEURAL NETWORK MODELING
The finite element model of the lens structure is established[6] and the following parameters are
determined as variables in the optimization design: the thickness of the back of the primary mirror
(using A representation) , the back of the secondary mirror (using B representation) , the thickness of
the back of the refractor (using C representation) , the thickness of the connecting end of the secondary
mirror of the extinction support cylinder using A representation (using D representation) , the thickness
of the inner shield wall (using E representation) , and the thickness of the connecting end of the shield
and the extinction support cylinder (using F representation) . Among these variables, the thickness of
primary and secondary mirrors refers to the depth of their lightweight holes. The positions of variables
in the lens are shown by 1-6 in Figure 2. The change of the first five parameters can be realized by the
change of the thickness of the 2D element of the finite element method. For the connecting end of the
shield and the extinction support cylinder, as shown in the red circle part of the Figure 5, if it is
modeled by the 2D element, it is impossible to accurately simulate the connection between the part
and the inner shade and the support cylinder, thus affecting the accuracy of the model. In this way, a
3D unit is established for this part, and the thickness change is realized by HYPERMORPH function.

After the structural design and finite element modeling are completed, the dynamic optimization
simulation of the lens is studied. According to the introduction of the above mathematical model, the
optimization model of the lens in this paper is as follows.

1) Objective function
The objective function $f(x)$ is the weight of the whole machine, and the optimization time is the
minimum. That is:
$$f(x) = \text{min}$$

2) Design variables
The design variables in this paper are the thickness of five 2D elements and the thickness of the
connecting end of the hood.

3) Constraint conditions
Fundamental frequency constraint:
$$f_{\text{max}} \geq f_{1} \geq f_{\text{min}}$$
Among them, \( f_{\text{min}} \) is the minimum required for the fundamental frequency. According to the overall index of the camera, \( f_{\text{min}} = 180\text{Hz} \); \( f_{\text{max}} \) is the maximum of the fundamental frequency proposed in the structural design. The purpose of this value is to avoid the redundancy of the stiffness and make the structural design more reasonable. This paper takes it as 220 Hz.

In addition, the objective of the optimization is to reduce the weight of the lens. It requires that the weight of the optimized structure should not exceed the original design weight \( W_0 \), so there is a self-weight constraint:
\[
W \leq W_0
\]

Dynamic optimization design is divided into two processes[7]. First, the dynamic model of the structure is established. Second, a reasonable optimization method is selected to optimize the structure. Its basic flow chart is shown in the Figure 6. In this paper, the dynamic model of structure is established by using BP neural network model.

BP network needs to train input data and output data to establish mapping relationship. In the neural network model, the input data are the above design variables, and the output data are the lens weight and the first-order frequency, respectively, according to the requirements of the objective function and constraints.

![Figure 6. Flow chart for optimization of neural network and genetic algorithm](image)

According to the rule of orthogonal test[8], six design variables are assigned three levels, and then 27 orthogonal test are done to construct the neural network with data of different levels as input. Variables and their levels are shown in Table 1.

| Levels | A(mm) | B(mm) | C(mm) | D(mm) | E(mm) | F(mm) |
|--------|-------|-------|-------|-------|-------|-------|
| 1      | 5     | 8     | 5     | 10    | 2.5   | 5     |
| 2      | 2     | 4     | 2     | 5     | 2     | 2     |
| 3      | 8     | 12    | 8     | 15    | 4     | 8     |

There are 27 sets of input-output data, and it is not necessary to list them all. In this paper, neural network modeling is performed based on these 27 sets of data, and 6 sets of data are listed as schematics. The schematic table is shown in Table 2.

| number | A(mm) | B(mm) | C(mm) | D(mm) | E(mm) | F(mm) | Mass(kg) | Frequency(Hz) |
|--------|-------|-------|-------|-------|-------|-------|----------|--------------|
| 1      | 5     | 8     | 5     | 10    | 2.5   | 5     | 270.42   | 1.827        |
After the construction of the neural network, the neural network is trained and tested\cite{9}. In this paper, according to the three levels of the six design variables mentioned above, another nine sets of data are selected to test the trained neural network. The predicted value comes from the output of nine sets of test data according to the mapping relationship, which is to be calculated. The expected value is the actual weight and fundamental frequency of nine sets of data in the finite element model, which are known quantities. In order to maintain the accuracy of prediction, this paper requires the root mean square error of weight parameters to be 0.01%, and the root mean square error of fundamental frequency parameters to be 0.5%.

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
  & 5 & 5 & 4 & 2 & 5 & 2 & 2 \\
10 & 2 & 8 & 5 & 15 & 2.5 & 2 & 190.73 & 1.718 \\
15 & 2 & 4 & 8 & 10 & 4 & 5 & 313.84 & 2.025 \\
20 & 8 & 8 & 8 & 5 & 2 & 5 & 264.17 & 1.824 \\
27 & 8 & 12 & 2 & 10 & 4 & 2 & 252.45 & 2.215 \\
\end{tabular}
\end{table}

Figure 7. Requirement of training accuracy

Set the training requirement accuracy to $1 \times 10^{-6}$. As shown in the figure 7, the training can achieve the desired effect after 36 iterations. After training, the test results in Figure 8 show that the black circle represents the predicted output of the neural network and the blue circle represents the actual output of the finite element. The root mean square error of weight is 0.076%, the root mean square error of fundamental frequency is 0.43%, which meets the training requirements. It shows that BP network has established a good relationship between input and output.

Figure 8. Expected output and actual output (weight on the left and base frequency on the right)
This paper takes weight as an example to further verify the modeling effect of BP neural network. The Figure 9 is the linear regression result of the training set and the test set. From this figure, it can be seen that the correlation between the predicted value and the actual value in the training set is 0.99999, and the correlation between the predicted value and the actual value in the test set is 0.99998. This also shows that the neural network model in this paper is well modeled.

4. THE RESULT OF DYNAMIC OPTIMIZATION BASED ON GENETIC ALGORITHM

After the successful neural network modeling, the lens needs to be weight-reduced. The mapping relationship between the input and output of the BP neural network model can’t be expressed by exact functions. Therefore, the traditional mathematical optimization method can’t be selected, and the genetic algorithm is used to optimize the neural network. According to the process shown in the figure 6, MATLAB is programmed to minimize the weight as the objective function, and the range of fundamental frequency is constrained from 180 Hz to 230 Hz. The genetic algorithm is used to optimize the neural network. The result of the optimization is shown in the figure 10.

![Figure 9. Linear regression results of training sets and test sets](image)

The figure 10 shows the iteration of the objective function. After 43 iterations, the objective function reaches the optimal solution, which is 1.677kg. At this time, the values of each variable are accurate to 0.001. Considering the processing precision, one decimal point is reserved for each variable. The initial data of each variable and the adjusted data are shown in the Table 3. By substituting the adjusted data into the neural network, the lens weight is 1.682 kg and the fundamental frequency is 189.37 Hz.

![Figure 10. iteration results of the optimization](image)

| Variable | A(mm) | B(mm) | C(mm) | D(mm) | E(mm) | F(mm) |
|----------|-------|-------|-------|-------|-------|-------|
| Original data | 5.562 | 5.131 | 3.787 | 8.324 | 2.788 | 4.474 |
| Modified data | 5.6 | 5.1 | 3.8 | 8.3 | 2.8 | 4.5 |

5. VERIFICATION OF OPTIMIZATION RESULTS IN FINITE ELEMENT

Through the finite element analysis, the lens weight is 1.687 kg and the fundamental frequency is 189.91 Hz with the same data. Its mode shape is shown in the figure. Compared with the finite
element model and the neural network model, the errors of weight and fundamental frequency are 0.30% and 0.29%, respectively. This proves that the optimization results are reliable and also meets the design requirements. At the same time, it shows that the design of this paper has accomplished the goal of lens weight reduction.

6. CONCLUSION
Aiming at the design requirement of low weight and high specific stiffness for a small space camera lens assembly, based on the coaxial four-mirror optical system chosen by optical designers, the initial lightweight design of lens structure is realized in an integrated assembly form. Secondly, taking some parameters of the lens as design variables, the size of the lens is optimized by using the neural network-genetic algorithm, which further reduces the weight. Finally, the finite element method is used to verify that the first-order frequency meets the requirements. It shows that the design goal of low weight and high specific stiffness of lens assembly is realized in this paper. The weight-loss design concept in this paper can be used for reference in the design of other aerospace structures.

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