**Structural Optimization Design of a Certain Aircraft Gun Closed Bearing Band Sabot Based on Variable Density Method**

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**Abstract.** As the aircraft has a high overall weight requirement, it is indispensable to make lightweight design of aircraft gun. The structural optimization design of a certain aircraft gun closed bearing band sabot is studied based on the variable density method. And a new structure of the sabot is obtained. The structural unit density and minimum flexibility are taken as design variable and objective function. The volume reduction percentage, equilibrium equation and engineering manufacturing are taken as a constraint. The results of finite element analysis on the optimized sabot structure show that the weight of the sabot is reduced by 9.7%. And the stiffness and strength of the optimized structure are slightly increased. The aim of lightweight design is realized, and the feasibility of topology optimization design is proved. The conclusion from this research is that it has engineered application value for the structure improved design of aircraft gun, and also provides a design solution for other general mechanical structure problems.

1. **Introduction**

The requirement of aircraft gun feeding system is becoming higher and higher with the development of aircraft gun technology and continuously rising emissivity. The traditional ammunition belt feeding cannot meet the requirement of high firing speed, which has a large energy loss and poor reliability in the feeding process. At the same time, it has poor adaptability to automat with high emissivity due to its structural characteristics and rigid strength factors. Chainless ammunition supply technology is widely used in the field of small-bore artillery, which has the advantages of stable and reliable ammunition supply and suitable for high-speed shooting [1]. The chainless shell-feeding with closed bearing band is a linear series of projectiles that are connected linearly by a closed bearing band consisting of sabot. One end of the closed bearing band is stacked in an ammunition box with a drive device. The other end is combined with the automat to complete the matching of the feeding system of the automat and its automatic feeding [2]. The method of this ammunition supply has the advantages of simple structure and realizable irregular space arrangement.

The lightweight is an issue that must be considered by aircraft guns because the aircraft generally has a high requirement for weight requirements. There is not much room weight loss for a certain aircraft gun automat and other parts. As a new design part, the chainless shell-feeding of closed bearing band has large weight reduction space, which is conservative in the process of designing. In addition, the number of sabot is a large quantity and a large proportion of weight, so it is possible to
realize the weight loss design by optimizing the structure of the closed bearing band sabot. The traditional design of weight loss through grooves and drill based on the experience of engineers, which are low efficiency, cycle length and high cost [3]. With the rapid development of applied mechanics, applied mathematics and computer technology, structural optimization technology has been developed rapidly, thus greatly shortening the product development cycle and reducing the design cost.

2. Analysis of rigid-strength of closed bearing band

The closed bearing band technology is a form of chainless ammunition supply. It is generally composed of driving device, closed bearing band, chain plate, sabot and projectile wheel, etc. The sabot is connected in pairs through a chain plate to form a closed bearing band at both ends to reciprocate cyclic delivery of projectiles, as shown in figure 1. When the wheel turns, the load of the sabot is the biggest, so this paper chooses the sabot 1 in figure 1 to carry on the force analysis. The sabot is affected by the pulling force $F_1$ generated by the driving wheel, pressure force $F_2$ generated by the projectile and supporting force $F_3$ generated by the projectile wheel. Force analysis of sabot is shown in figure 2.

There is seven-stage gear from the automat to the ammunition box, its total transmission ratio $i = 1.38$. The automat is running at 1000 $r/min$. Therefor, the ammunition box is running at 725 $r/min$. The radius $r$ of the projectile wheel is 25mm, by formula

$$v = \omega \cdot r$$

$$\omega = 2\pi n$$

The linear velocity of the sabot can be calculated to be $v = 1.89 m/s$. The time of aircraft gun from start to steady rate of fire is 0.1s. The ammunition belt moves in a straight line at constant speed after the fire rate of automat is stabilized. The velocity on the ammunition belt increases from 0 to 1.89 $m/s$, and the impulse formula is used to obtain the pulling force in $F_1$.

$$F_1 = m\Delta v$$

Maximum pulling force on the chain plate is calculated to be $F_1 = 3.2N$, the weight of the projectile is 0.7kg, the pressure on the projectile holder can be calculated to be $F_2 = 7N$. Static analysis of the sabot is carried out, and the results are shown in Fig 3-4.

![Figure 1. Local structure of a certain aircraft gun closed bearing band](image1)

![Figure 2. Force analysis of sabot](image2)

![Figure 3. Displacement nephogram of sabot](image3)
3. Topological optimization of variable density method

3.1. Mathematical model of topological optimization with variable density method

Structural topology optimization [4] is a structural design method, which determines the optimal load path of the material in the specified design space according to the known working conditions and boundary constraints, so that the structural rigid and the strength can meet the specified requirements. At present, there are mainly homogenization method, variable density method and evolutionary structural optimization method in the related research of structural topology optimization. Because the variable density method program is simple to realize and has high computational efficiency, it has been widely used in engineering practice. The basic idea of the variable density method is to introduce an imaginary density variable material into the element, and assume that the density of the variable material is between 0 and 1, and then establish a nonlinear correspondence between the element density and the elastic modulus of the material. By introducing penalty factor to punish the intermediate density value can avoid generating units between 0 and 1, and the intermediate density value is gradually aggregated to 0 or 1. Finally, the unit of density of 0 is removed, and the unit of density of 1 is retained. The structure of the design area is clear and the geometric shape is easy to be designed and realized.

There are design variable, objective function and constraint condition three essential factors in optimal design. A design variable is a set of parameters that change during optimization to improve performance. Objective function that is a function of design variables requires optimal design performance. Constraints are limits to design and requirements for design variables and other performance. In this paper, the element density is taken as the design variable. The volume constraint and the equilibrium equation are taken as the constraint conditions. And the minimum flexibility is taken as the objective function. The topological optimization mathematical model of the variable density method is established as follows:

\[ \text{Find:} \quad \rho = \left( \rho_1, \rho_2, \ldots, \rho_N \right)^T \in \mathbb{R}^n, \quad i = 1, 2, \ldots, N \]

\[ \text{Minimize:} \quad C = U^T K U = \sum_{e=1}^{N} u_e^T k_e u_e = \sum_{e=1}^{N} \left( \rho_e \right)^{\nu} u_e^T k_0 u_e \]

\[ \text{Subject to:} \quad V = f \cdot V_0 = \sum_{e=1}^{N} \rho_e v_e \leq V^* \]

\[ F = K U \]

\[ 0 \leq \rho_{\text{min}} \leq \rho_e \leq \rho_{\text{max}} \leq 1 \] (4)

In the formula, \( \rho \) is a design variable; \( \rho_e \) is an element design variable; \( C \) is an overall flexibility of the structure; \( U \) is a displacement array; \( K \) is a global stiffness matrix; \( u_e \) is an element displacement matrix; \( k_e \) is an element stiffness matrix; \( p \) is a penalty factor; \( V \) is optimized structural volume; \( V_0 \) is the initial volume of the whole design space; \( v_e \) is the unit volume after optimization; \( f \) is the volume ratio before and after the optimization; \( F \) is the load matrix; \( \rho_{\text{min}} \) and \( \rho_{\text{max}} \) are the minimum limit...
value and the maximum limit value of the relative element density; The purpose of introducing $\rho_{min}$ is to prevent the singularity of the element stiffness matrix [5].

3.2. Method of optimality criteria

At present, the main solution algorithms for structural optimization are the method of optimality criteria and mathematical programming. The method of optimality criteria that satisfied the Kuhn-Tucker condition is established based on the principle of structural mechanics, which select the strength, stiffness and stability of the structure as the objective function and under the condition satisfying the constraint conditions (such as stress, displacement, frequency, etc.). And then, an iterative formula for optimal design is established according to the optimality criteria. The method of optimality criteria has the advantages of efficient convergence, few iterations, and the number of re-analysis is independent of the number of design variables and the complexity of the structural model. It has very high efficiency for solving topological optimization problems with volume constraint as the constraint function and minimum flexibility as objective function. In this paper, the method of optimality criteria is used to solve the structural optimization of the sabot [6].

For the topological optimization problem of variable density method in (4) the Lagrangian equation is as follows:

$$L = C + \lambda_1 (V - f \cdot V_0) + \lambda_2 (KU - F) + \lambda_3 (\rho_{min} - \rho + h_2^2) + \lambda_4 (\rho - \rho_{min} + c_i^2)$$

(5)

In the formula, $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$ is a Lagrangian multiplier; $\lambda_1$ is scalar; $\lambda_2$, $\lambda_3$, $\lambda_4$ is vector; $b_i$, $c_i$ is relaxation factor; $\rho$ is a column vector composed of $\rho_i$; When the extreme value of $\rho_i$ is taken, Lagrange function satisfies Kuhn-Tucker theorem, so that the optimality criteria can be derivation [7]:

$$C_e^k = p\left(\rho_e\right)^{p-1}u_e^T k_e u_e = 1$$

(6)

According to the upper and lower limits of the design variables of the optimality criteria, the iteration formula based on the optimality criteria can be obtained as follows:

$$\rho_e^{k+1} = x_{min} \quad \text{If} \quad \left(C_e^k\right)^q \rho_e^k \leq \rho_{min}$$

$$\rho_e^{k+1} = \left(C_e^k\right)^q \rho_e^k \quad \text{If} \quad \rho_{min} < \left(C_e^k\right)^q \rho_e^k < \rho_{max}$$

$$\rho_e^{k+1} = \rho_{max} \quad \text{If} \quad \left(C_e^k\right)^q \rho_e^k \geq \rho_{max}$$

(7)

In the formula, $\eta$ is a damping coefficient, and the stability and convergence of the numerical calculation can be ensured by introducing the $\eta$ .

4. Topology optimization analysis of closed bearing band sabot based on variable density method

As showed in figure 5, the red part is the design space of the sabot, which the material can be removed, and the green part is the non-design space of the sabot, which the material needs to be retained.

![Figure 5. Design space of the sabot](image)
After topology optimization analysis, we need to refer to the results of topology optimization to carry out complex geometric reconstruction, however, it seldom considers the subsequent engineering requirements in the process of topology optimization. In addition, due to the instability of numerical calculation in topology optimization, the result of topology optimization is not an engineering feasible solution. Therefore, before the topology optimization analysis, it is necessary to add manufacturability constraints to produce the practical value of the manufacturability results. Minimum and maximum member size and checkerboard constraints can avoid fine structural features, material stacking and checkerboard phenomena in the optimization results. Drawing and pattern grouping can be used to produce structures that conform to the processing technology. The optimal setting parameters for the sabot are shown in Table 1.

Table 1. Optimization settings

| Optimization type | Topological optimization |
|------------------|--------------------------|
| Minimum member size | 8mm |
| Maximum member size | 16mm |
| Draw type | single draw |
| Symmetric type | 1-pln sym |
| Response type | Flexibility; Volume fraction |
| Constraint | Volume fraction 0.4 |
| Optimization objective | Minimum flexibility |

After setting design variables, objective function and constraint function, the software will automatically carry out several material removal attempts according to the conditions settings. And make static analysis of the model after removing the material, and verify that its performance meets the optimization constraints and the constraints of the optimization objectives. The topological optimization density cloud diagram of unit density greater than 0.3 is shown in figure 6. The sabot iterated curve of objective function is shown in Fig 7. The sabot iterated curve of constraint function is shown in Fig 8.

From the iterated curve of objective function in the figure 7 can be known the flexibility of the sabot is reduced continuously, and the convergence state is reached after 29 iterations in the process of
iterative calculation. The flexibility of the sabot is gradually reduced from the initial $0.143 \text{ mm} \cdot \text{N}^{-1}$ to $0.9 \text{ mm} \cdot \text{N}^{-1}$. From the iterated curve of constraint function in the figure 8 can be known about the variation of volume percentage of sabot during iterative calculation. The sabot’s volume percentage always fluctuates around 0.4 during the iteration. And the volume fell by 60% compared with the initial volume of the sabot. From the density cloud diagram of unit of sabot in the figure 6 can be known that the optimized structure is symmetrical along the middle plane of the sabot bracket and the shape of the structure is regular and the processing technology is good.

5. Manufacturability improvement
Because topology optimization is only a conceptual design, the optimization results have many small irregular surfaces, which cannot be used in machining and manufacturing, so it is necessary to carry out manufacturability improvement according to the optimization results. In this paper, the optimized result is introduced into CREO software, and the material is removed and the new structural form is determined according to the result of topology optimization. Finally, the finite element analysis of the new structure is carried out. The new structure of sabot is shown in Fig. 9 and the result of finite element analysis is shown in Fig 10 and Fig 11.

The comparison of parameters before and after optimization is shown in Table 2. From table 2 shows that compared with the original sabot structure, the weight of the optimized structure is reduced by 9.7%, and the maximum deformation is reduced by 0.4%, indicating that the stiffness of the optimized structure is basically unchanged. The maximum stress of the optimized structure is reduced by 1.5%, indicating that the strength of the optimized structure is improved.

Table 2. Comparison of sabot before and after optimization

|                  | Original structure | New structure | Change rate |
|------------------|-------------------|--------------|-------------|
| Displacement (mm)| 0.000266          | 0.000265     | -0.4%       |
| Stress (MPa)     | 1.33              | 1.31         | -1.5%       |
| Mass (g)         | 176               | 159          | -9.7%       |
6. Conclusions
In this paper, the topology optimization method is used to study the topology optimization of the closed bearing band sabot of a certain aircraft gun, which solves the limitation of the previous empirical design. Compared with the original structure, the weight of the sabot is reduced by 9.7% and the stiffness and strength of the optimized structure is slightly increased. The aim of lightweight design is realized, and the feasibility of the topology optimization design is proved. It is conclusion that it has engineered application value for the structure improved design of aircraft gun, and also provides a design solution for other general mechanical structure problems.

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