Lightweight Design of Hinge Based on Topology Optimization

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Abstract. The topology optimization method has become an effective method to solve the structural optimization problem due to its advantages in weight reduction, material saving and cost reduction. Hinge is a commonly used connector with wide application occasions, large demand, and high reliability requirements. It needs to meet the strength requirements while carrying out lightweight design. In this paper, the refrigerator hinge is taken as the object, the topology optimization of the hinge is carried out by introducing manufacturing process constraints, the model is reconstructed according to the result of the topology optimization, and finally the reconstruction model is analyzed by finite element. The results show that under the premise that the hinge meets the requirements of strength, its own weight and maximum stress are reduced, and the weight reduction rate reaches 13.1%, which achieves the purpose of lightweight hinge design. This method can provide a basis for the evaluation and optimization of the initial design scheme of the hinge, and can also provide a way of thinking for the optimization of other structures.

1. Introduction

Hinge is a commonly used connector with very wide application, large demand, and high reliability requirements. In the development process of hinge products, it is necessary to meet the strength requirements and the reliability requirements of hinges while reducing weight, saving materials, and reducing costs by reducing materials. Minsoo Kim [1] proposed using the equivalent static load method to establish the equivalent static load model of the refrigerator hinge under impact load for topology optimization design. Benliang Zhu [2] proposed a systematic method for topology optimization of winding hinges using the level set method. Gayno Andrew [3] proposed a design and manufacturing process to achieve three-phase and multi-material compliance mechanisms for topology optimization. Zhijun Yang [4] proposed to transform the topology and size optimization problem into an analytical optimization formula with discrete and continuous variables to find the best topology and corresponding size of the flexible hinge. In the hinge optimization process, generally by increasing the wall thickness of the hinge plate or increasing the shaft diameter of the hinge shaft, the purpose of improving the strength of the hinge is achieved, but the weight of the hinge is greatly increased and the cost is increased.

The refrigerator hinge connects the refrigerator box and the door, and its locking effect will directly affect the position of the door. In the process of using the refrigerator, the hinge not only has to bear
the weight of the refrigerator door body and the weight of the load on the door, but also is affected by
the impact load when opening and closing the door [5]. Insufficient hinge strength will cause structural
damage and deformation, resulting in failure of the refrigerator door to be completely closed or
poor sealing to create gaps, and the occurrence of cold leakage, which affects the refrigerator's cooling
effect and causes unnecessary energy consumption. Therefore, the lightweight design of refrigerator
hinges is very important. This paper takes it as the research object to carry out finite element analysis,
adopts topology optimization design method to design the refrigerator hinge lightweight, with the
ultimate goal of reducing the weight of the hinge and the maximum stress, and compares the analysis
results of the original model and the optimized model. Review and evaluate the results obtained by
optimization.

2. Theoretical basis of topology optimization

2.1. Topology optimization model

Topology optimization is to make the design as a whole to achieve the best effect [6]. It is currently a
popular structural lightweight technology, which converts the problem of how to achieve the optimal
structure into a problem of how to achieve the optimal material distribution according to the load on
the model and its boundary conditions [7]. Topology optimization is mainly to divide the design area
into grid cells, and then carry out structural analysis [8]. Remove some units from it in a specific
optimization method, use the remaining units to describe the optimal topological structure of the
research object, and achieve the purpose of changing the material distribution by iteratively calculating
all material density units, so as to achieve light weight while meeting certain performance
requirements [9]. Compared with other lightweight design methods, topology optimization can obtain
greater design space and design freedom.

In practical engineering applications, by setting the manufacturing process constraints in the
topology optimization design, the optimization results can not only meet the structural performance
indicators, but also meet the actual processing technical indicators of the product [10]. Commonly
used manufacturing process constraints include member size constraints, draft constraints, minimum
aperture constraints, extrusion constraints, and symmetry constraints [11]. This paper mainly
introduces the manufacturing process constraints of the smallest member size to optimize the
refrigerator hinge topology. The minimum member size constraint is one of the most commonly used
constraints to control the minimum length scale of the model structure, and it has been implemented in
many projects. This constraint can ensure the minimum size value of the optimization model, avoid
the appearance of small holes and other structures, and solve the non-uniqueness and gray scale of the
solution in the optimization process. The mathematical description of the minimum member size
constraint is shown in Equation(1):

\[ L = \sum_{i=1}^{N} S_i \rho_i / l_{d_i} \geq L^* \quad (1) \]

In the formula, \( L \) is the equivalent characteristic value of the boundary size of the small structural
unit, \( N \) is the number of discrete units, \( \rho_i \) is the unit density value of \( i \), \( S_i \) is the unit external surface
area value of \( i \), \( l_{d_i} \) is the projected average depth, and \( L^* \) is the lower bound of the size.

In the process of topology optimization, because the objective function is generally a non-linear
function, the design domain is a non-linear space, resulting in the actual optimization feasible region
being much smaller than the theoretically setting feasible region. Usually, the convex optimization
method is used to approximate the topology optimization model, but as the complexity of the
optimization model increases, it is easy to cause the feasible solution to often not meet the actual needs
of the project. In order to obtain a topological optimization structure that is easy to manufacture and
process, the manufacturing process constraints are introduced, and the mathematical model is as in
Equation(2):
In the formula, \( g_j(\rho_i) - g^* \leq 0, \) \( H(\rho_i) = 0 \) and \( g(\rho_i) - g^* \leq 0, \) \( h(\rho_i) = 0 \) are manufacturing process constraints, \( \rho_i \) is the design variable of element \( i, \) \( j \) is the number of corresponding constraints, \( C(\rho) \) is the flexibility of a given topology. \( U \) is the displacement vector of the element node, \( K \) is the global stiffness matrix, \( F \) is the load vector of the element node, \( V(\rho) \) is the optimized structural volume, \( f \) is the preset volume fraction, and \( V_0 \) is the volume of the design domain. \( \rho_i \) is a design variable and \( \rho_{\min} \) is a vector containing the lowest allowable relative density.

### 2.2. Optimization criterion method

In order to obtain ideal topology optimization results, appropriate numerical calculation methods are required. At present, the most widely used mathematical solving algorithms for topology optimization include optimization criterion method, mathematical programming method and random search method. The optimization criterion method is a method that stipulates the optimal criterion that can deal with the corresponding constraints according to the optimal conditions of mechanics principles and mathematical programming, and establishes an optimization iterative mathematical model based on. According to the Kuhn-Tucker condition, an optimization iterative formula is established, and the constraint condition is combined with the objective function and then converted into a zero constraint problem [12]. In this paper, the optimization criterion method is used to optimize the topology of the hinge mechanism of the refrigerator, which is applied in the OptiStruct solver of HyperWorks.

The main realization method of the optimization criterion algorithm is to obtain the Lagrange equation by combining the objective function and the preset constraint condition, and the constraint condition and the objective function are combined into an unconstrained problem. The mathematical model of the optimization criterion method of the objective function can be expressed as in Equation(3):

\[
L = \lambda_1 (V - fV^*_0) + \lambda_2^T (KU - P) + \sum_{i=1}^{n} \lambda_i (\rho_{\min} - \rho_i) + \sum_{i=1}^{n} \lambda_i (\rho_i - 1) + C
\]  

(3)

In the formula, \( \lambda_1, \lambda_2, \lambda_3 \) and \( \lambda_4 \) are all Lagrange multipliers.

The optimization criterion method can calculate the elements of the design domain at the same time, find the main path of stress transfer at the fastest speed, and can solve the topology optimization problem of large-scale design variables. The optimization criterion method is generally obtained by Kuhn-Tucker optimal conditions [13]. The optimization iterative formula established by the K-T condition is as in Equation(4):

\[
\begin{align*}
\frac{df(\rho^*)}{d\rho_j} + \sum_{j \in J} \mu_j \frac{dg_j(\rho^*)}{d\rho_j} &= 0 \quad (i = 1, 2, \ldots, n) \\
g_j(\rho^*) &= 0, \quad \mu_j \geq 0 \quad (j \in J)
\end{align*}
\]  

(4)

The optimization criterion method has the characteristics of fast iterative convergence and small calculation amount. It does not become complicated with the increase of structural complexity and design variables. It is widely used in large-scale structural optimization. The design variable iteration formula can be expressed as in Equation(5):
In the formula, \( t \) is the translation limit and \( \omega \) is the damping coefficient, and \( t \) is equal to 0.2, and \( \omega \) is equal to 0.5. Two parameters are used to control iteration stability and rapid convergence. \( B_e = (-\frac{\partial C}{\partial \rho_e})/\xi \) is an intermediate variable and \( \xi \) is a Lagrangian multiplier. The value is generally determined by the dichotomy.

3. Hinge topology optimization design
Simplify the model by analyzing the structure of the hinge, define the material properties of the hinge, and preprocess the optimization object. Set the topological optimization conditions for the hinge and select the design area. The OptiStruct solver in HyperWorks is used to perform finite element analysis on the hinge, extract the topology optimization model, reconstruct the hinge model, and finally perform finite element analysis on the reconstructed model [14]. The entire optimization process is shown in Figure 1.

![Flow chart of the optimization process](image)

Fig. 1 Flow chart of the optimization process

3.1. Simplification and mechanical analysis of hinge structure
The refrigerator is mainly composed of a cabinet and a door. The door is often opened and closed when the refrigerator is in use, and the hinge plays an important role in the process of opening and...
closing the door. The hinge connects the rotating door body and the box body. The hinge structure is completely constrained on the box body during operation. The door body is opened and closed through the hinge shaft. The refrigerator model and the hinge position are shown in Figure 2. In terms of structural composition, the hinge is mainly composed of a hinge plate and a hinge shaft, which are connected by riveting or welding. During the assembly process, the hinge shaft extends into the refrigerator door, and the hinge plate is usually directly fixed on the refrigerator box by screws [15].

![Fig. 2 Refrigerator model and hinge position](image)

The hinge is a key component, which can fix the structure of the door and play the role of connection. The hinge is mainly used as the research object to ignore the influence of the additional connection structure. The hinge not only has to bear the weight of the door body and the weight of the attachments on the door, but also will be impacted by external forces during the door opening and closing process, and the load is mainly concentrated on the upper end of the rotating shaft. In order to reduce the amount of calculation in the optimization design and improve the quality of the mesh, the geometric features of the hinge as a whole are simplified. Remove the small features that have little effect on the stress distribution, such as chamfers and fillets. The simplified hinge model is shown in Figure 3.

![Fig. 3 Simplified hinge model](image)

Because the center of gravity of the refrigerator door does not coincide with the hinge support position, the middle hinge will bear axial and radial loads at the same time. By analyzing the working conditions of the hinge during the load-bearing process, the upper shaft end is determined to be the concentrated stress part, and the following three working conditions are considered as the load conditions for the optimal design of the hinge structure. The specific working conditions are as follows:

In the first condition, the upper shaft end receives an axial force of 10N in the positive Z direction. In the second condition, the upper shaft end receives a radial force of 6N in the positive X direction. In the third condition, the upper shaft end receives a radial force of 4N along the positive Y direction.
3.2. Treatment before hinge optimization

The topological optimization of components selects shell elements or solid elements according to their characteristics to define the space to be designed. Because this hinge has a thickness of only 2.5 mm and a small size, the hinge body uses the shell element feature. Divide the non-design domain to avoid excessive additional bending stress. 2D meshing is performed, which can shorten the solution time. The hinge body and the rotating shaft are rigidly connected, and the deformation of the shaft is not considered. The shaft and the inner wall of the hole are all simplified by rigid units. Define the material characteristic parameters of the hinge, and apply the loads of the three working conditions to the simplified meshed model. The effect of the pre-processing is shown in Figure 4.

Fig. 4 Pre-processing effect diagram

Through finite element calculation, the displacement result obtained is used as the constraint condition for topology optimization design. The displacement and stress contours of the original model under different working conditions are shown in Figure 5. It can be seen from the figure that under the first working condition, the maximum displacement of the hinge is 4.125x10^{-5}mm, and the maximum stress is 0.366MPa. After analysis, the hinge displacement is not large, but the force on the joint between the hinge plate and the hinge shaft is relatively large. Under the second working condition, the maximum displacement of the hinge is 2.584x10^{-3}mm, and the maximum stress is 1.937MPa. After analysis, the straight notch of the hinge body is relatively large in force. In the third working condition, the maximum displacement of the hinge is 1.529x10^{-3}mm, and the maximum stress is 1.507MPa. After analysis, the hinge bend plays a major role in resisting bending and bearing, and its stress is relatively large, which is prone to material deformation.

(a) The first working condition
3.3. Hinge topology optimization

The OptiStruct solver of HyperWorks is used to realize the topology optimization analysis process of the hinge. OptiStruct is a finite element and structural optimization solver based on the optimization criterion method. It mainly conducts product design, analysis and optimization, and obtains the optimal solution through small step iterations.

Carry out optimization analysis on the hinge, define the limit load condition, determine the load mode during topology optimization as static load, and carry out static analysis. Comprehensively consider the stress conditions of each working condition, refer to the stress cloud diagram of the simplified model under various working conditions, and define the unique constraints under different working conditions. In order to make the structure lightweight and achieve better results and prevent the appearance of small holes and other structures in the topology optimization results, the minimum member size in the manufacturing constraints is introduced. The minimum member size is at least three times the average of the density element size. This model sets the minimum member size to 10mm and the maximum number of iteration steps to be 100 times. By running the solver for optimization calculation, the structure shows that the convergence effect of the objective function is better when the objective function is iterated 31 times. The topology optimization result obtained by setting the current value to 0.3 is shown in Figure 6.

Fig. 5 The original model displacement and stress cloud diagram

(b) The second working condition

(c) The third working condition
3.4. Hinge model reconstruction
According to the results of hinge topology optimization, the original hinge structure is modeled and reconstructed. Part of the area on the left side of the hinge body and the upper right of the circular hole of the vertical plate can reasonably remove part of the material. The hinged bottom plate is very important in terms of force and fixation, so the other parts of the bottom plate are retained. The hinge vertical plate part is hollowed out, and the straight notch and the round hole are added with bosses for reinforcement. The rest of the structural units retain the original structural features, and finally the hinge reconstruction model is shown in Figure 7.

3.5. Finite element analysis of the reconstructed model
The reconstructed model is divided into meshes, related parameters are defined, limit load conditions are defined, and finite element analysis is performed on the reconstructed model through a solver. The displacement and stress cloud diagrams of the reconstructed model under different working conditions obtained by calculation and analysis are shown in Figure 8. It can be seen from the figure that in the first condition, the maximum displacement of the hinge reconstruction model is $3.110 \times 10^{-5}$mm, and the maximum stress is 0.230MPa. In the second working condition, the maximum displacement of the reconstructed model is $2.866 \times 10^{-3}$mm, and the maximum stress is 1.876MPa. In the third working condition, the maximum displacement of the reconstructed model is $1.682 \times 10^{-3}$mm, and the maximum stress is 1.156MPa.
4. Result analysis

By comparing the displacement and stress cloud diagrams of the original hinge model and the reconstructed model, the displacement and stress comparisons of the original model and the reconstructed model under the same working conditions are shown in Table 1. It can be seen from the table that under the same load, the maximum stress of the optimized model under the same working conditions is reduced compared with the original model, which meets the maximum stress requirement of material structure optimization. In the first working condition, the maximum displacement and stress of the reconstructed model are reduced, and the maximum stress reduction rate reaches 37.2%. In the second working condition and the third working condition, the maximum displacement is slightly increased. However, the maximum stress has been reduced, and the reduction rates are 10.9% and 3.1% respectively. It shows that the optimized model has improved the stiffness of the hinge, and also improved the ability of the hinge to resist deformation when it is loaded.
### Table 1. Displacement and stress comparison of the model before and after optimization

| Force condition       | Parameters for comparison | Original model | Optimization model | Amount of change |
|-----------------------|---------------------------|----------------|-------------------|------------------|
|                       | Displacement (mm)         | 4.125x10^{-5} | 3.110x10^{-5}    | 1.015x10^{-5}    |
|                       | Stress (MPa)              | 0.366          | 0.230             | -0.136           |
| The first working condition | Displacement (mm)         | 2.584x10^{-3} | 2.866x10^{-3}    | 0.282x10^{-3}    |
|                       | Stress (MPa)              | 1.937          | 1.876             | -0.061           |
| The second working condition | Displacement (mm)         | 1.529x10^{-3} | 1.682x10^{-3}    | -0.153x10^{-3}   |
|                       | Stress (MPa)              | 1.507          | 1.156             | -0.351           |

Through the tool mass calc in HyperMesh, the theoretical quality of the original hinge structure model and the optimized reconstruction model have been measured. The mass before optimization is 12.69g, and the mass after optimization is 11.03g. The theoretical mass difference before and after optimization was 1.66g, and the reduction rate reached 13.1%. The results show that the lightweight design of the hinge structure based on topology optimization has ideal optimization effects in terms of mechanical properties and weight reduction, and the optimization results are relatively successful.

### 5. Conclusion

The structural optimization strategy based on topology optimization provides an optimization method and optimization idea for the lightweight design of various structures. In this paper, the lightweight design and research of the hinge on the refrigerator are carried out on the basis of topology optimization. The displacement, stress cloud and topology optimization results of the hinge model have been analyzed, and the secondary modeling and optimization design of the hinge have been carried out. Under the premise of meeting performance requirements, the optimized hinge has reduced weight and maximum stress. The product structure has been optimized, the properties of the product have been improved, the cost has been reduced, and the goal of lightweight hinge design and structural optimization has been achieved. The results show that the lightweight design based on the topology optimization method can provide a certain reference in the structural design. Improve the quality and performance of product structure, reduce development costs, and find a more reasonable design scheme. This method has certain guiding significance for the structure design of the refrigerator dumpling chain, and can be extended to the design of different types of hinge structures.

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