World Scientific Research Journal Volume 9 Issue 1, 2023
ISSN: 2472-3703 DOI: 10.6911/WSRJ.202301_9(1).0001

Multi-objective Topology Optimization of Missile Launcher Pitching Structure Based on Variable Density Method

Yongkang Li, Jinghua Tai, Yongsheng Yang, Xilei Zhao

The 713th Research Institute of China Shipbuilding Industry, line 2-name of organization, acronyms acceptable Zhengzhou, China

Abstract

In order to evaluate whether the design of the missile pitching structure meets the requirements, A three-dimensional solid model of the missile launcher is established in Creo,and the stess and deformation analysis of the type of pitching structure under typical operating conditions is completed by using the finite element software. According to the load-bearing and launch accuracy requirements, the finite element optimization models of three typical box-bomb configurations were established, and the topology optimization of the pitching structure was carried out with the objective of minimizing the weighted flexibility, and the optimized model of the pitching structure was obtained by combining with engineering applications. The stress and deformation of the pitching structure before and after optimization are compared and analyzed. The results show that the mass of the optimized pitching structure is reduced, and the stress concentration is significantly improved, which satisfies the requirements of rigidity and strength well.

Keywords

Pitching structure; Variable density method; Multi-objective topology optimization; Emission accuracy.

1. INTRODUCTION

Missile launcher is an important part of missile weapon system [1]. Taking a missile launcher as an example, the launch box is installed on the pitching frame through the locking support angle. The pitching frame needs to bear the gravity of the box bomb and the impact of gas flow after the missile is launched out of the box. Therefore, the stiffness and strength of pitching frame is an important factor affecting the reliability of missile launcher and missile launch accuracy.

For a long time, the design of launcher is mainly based on engineering experience, and it needs to go through repeated design and verification, which lengthens the design cycle of launcher structure [2]. At the same time, the traditional design method is conservative and has a large safety factor, which will inevitably lead to material waste and cost increase. Therefore, it is necessary to introduce new design ideas to improve design efficiency and reduce design cost. With the gradual enrichment and improvement of structural optimization design theories and methods, coupled with the rapid development of computer-aided engineering technology, virtual prototypes and simulation analysis have gradually replaced traditional physical prototypes and experimental explorations, such as structural topology optimization and meshless simulation analysis. Various simulation analysis methods are becoming more mature and widely used. Among them, topology optimization is a technology to find the best material distribution under certain constraints in a specific region. Commonly used methods include homogenization method, variable density method and level set method [3-5]. In particular, the variable density method has high operation efficiency and good robustness, and has wide applicability in engineering structure design.

In this paper, the variable density method is used to optimize the multi-objective topology of the pitch frame of a certain type of missile launcher under a variety of typical loading conditions: a single set of box shells are placed in the center, a single set of box shells are placed on one side, and two sets of box shells are placed on both sides. Design and compare and analyze the pitch frame structure before and after optimization. The analysis results show that the multi-objective topology optimization method using the variable density method effectively reduces the weight of the pitch frame, improves the rigidity of the pitch frame, and provides a scientific design method for the structural design of the launcher.

2. ESTABLISHMENT OF THE PITCH FRAME MODEL

2.1. Tilt frame model

A missile launcher consists of a launch box (including a missile), a slewing and pitching device, a base, a control system, software and auxiliary equipment [6]. The slewing and pitching device is composed of a slewing frame and a pitching frame, which is used to support the missile launch box and provide the initial pointing angle for missile launch.As an important component of the slewing and pitching device, the pitching frame realizes reliable locking and pitching movement of the launching box. The three-dimensional solid model of the pitching frame is shown in Figure 1.

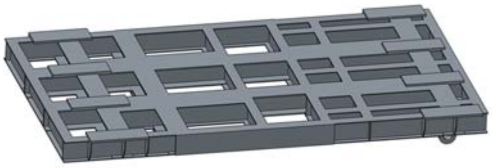


Figure 1. Model of pitching structure

2.2. Apply constraints and loads

The launcher shall be reasonably simplified and the key components shall be retained, mainly including launch box (including missile), pitching frame, slewing frame and base. The pitching frame, slewing frame and base are made of steel, with an elastic modulus of 206gpa and a Poisson's ratio of 0.3.Establish the multi-body finite element calculation model of the launcher. As shown in Figure 2, the tail of the pitching frame is connected with the slewing frame through trunnions, and the two trunnions on the front side are connected with the vertical cylinder, which drives the pitching frame to complete the pitching motion. The revolute joint established at the rear trunnion of the pitching frame is hinged to simulate, the lifting cylinder is equivalent to a rigid body, and the front trunnion is simulated by the spring joint.

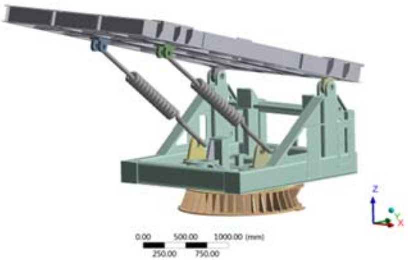


Figure 2. Multi-body finite element model of the launcher

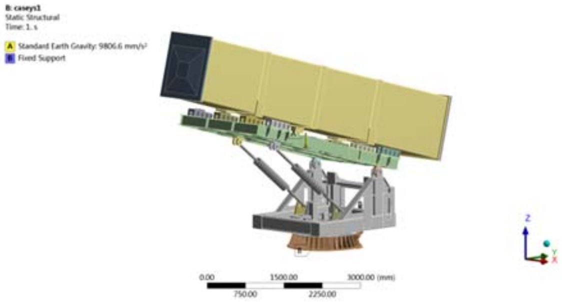
This article analyzes the structural strength of the launcher for the following three working conditions.

Working condition 1: The single set of ammunition box is placed in the center.

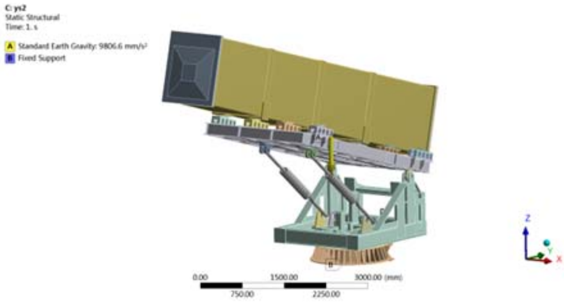
Working condition 2: Single set of ammunition box placed on one side.

Working condition 3: Two sets of ammunition boxes are placed on both sides.

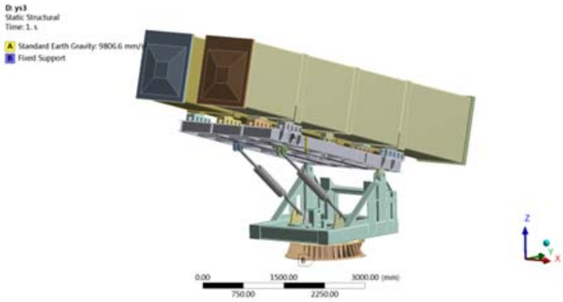
A fixed support constraint is applied to the bottom of the launcher base, and a gravity acceleration load is applied to the structure as a whole. The obtained calculation models under three working conditions are shown in Figure 3.



a) Single set of box bombs placed centrally



b) Single set of box bombs placed on one side

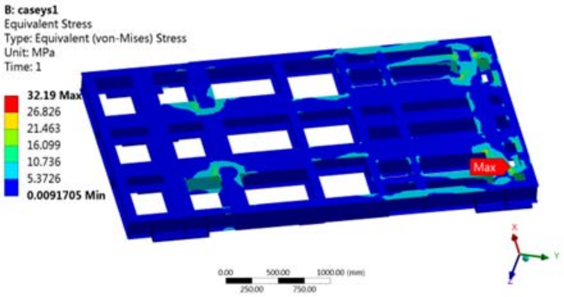


c) Two sets of box bombs placed

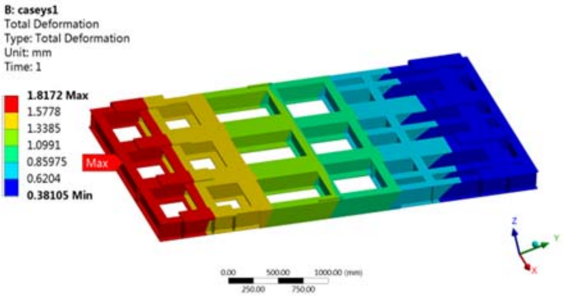
Figure 3. Calculation model diagram of three typical working conditions

2.3. Simulation result analysis

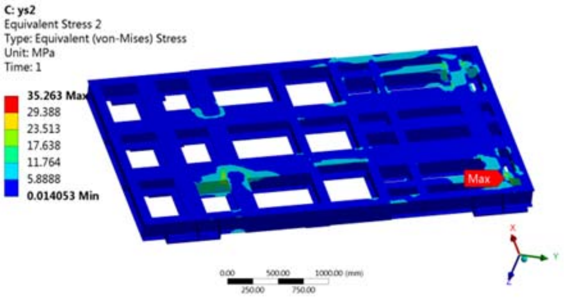
The stress and displacement nephogram of the pitching frame under three typical box bomb configurations is shown in Figure 4. After analysis, under three typical working conditions, the maximum stress of the pitching frame is 45.88mpa, which is located at the reinforcing plate near the rear trunnion of the pitching frame; The maximum displacement is 2.55mm, which is located at the front end of the pitching frame. According to the stress nephogram, the parts with large stress of the pitching frame are mainly located near the front and rear trunnions of the pitching frame, and the stress values at other positions are at a low level, indicating that the transverse and longitudinal stiffeners arranged on the pitching frame fail to realize the effective transfer of load. Therefore, it is necessary to carry out topological analysis on the pitching frame structure, optimize the layout of transverse and longitudinal stiffeners on the pitching frame, and improve the utilization rate of materials.



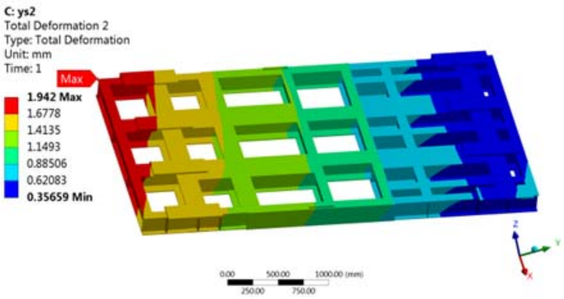
a) Stress of pitching structure
(Working condition I)



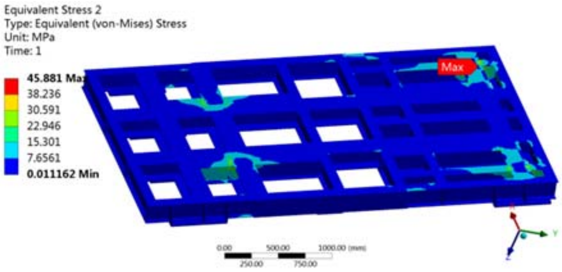
b) Displacement of pitching structure
(Working condition I)



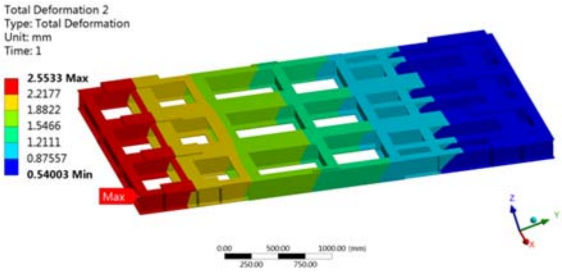
c) Stress of pitching structure
(Working condition II)



d) Displacement of pitching structure
(Working condition II)



e) Stress of pitching structure
(Working condition III)



f) Displacement of pitching structure
(Working condition III)

Figure 4. The stress and displacement cloud diagram of the pitch frame under three typical working conditions

3. MULTI-OBJECTIVE TOPOLOGY OPTIMIZATION MODEL OF PITCH FRAME STRUCTURE

3.1. Variable density interpolation

Topology optimization of pitching frame belongs to topology optimization of continuum structure [7]. The material distribution in the design area is expressed by density value, and the value interval is [0,1]. The density value of each unit in the design area is taken as the design variable, and the optimal material distribution in the design area of pitching frame is taken as the mathematical objective on the premise of satisfying the constraint conditions.

The mathematical relationship between elastic modulus and element material density is established by defining the following formula [8]:

$$E_i=\rho_i^p E_0 \quad \left(i=1,2\ldots n\right) \tag{1}$$

In the formula, E_i represents the elastic modulus of unit i in the design area, E_0 corresponds to the elastic modulus when the unit material density is 1, and p is the penalty factor, which penalizes the intermediate density of the unit material to make the unit material density as close as possible At "0" or "1".

For the three-dimensional pitching frame model, the value of p is as follows:

$$p \geq \max\left\{15\frac{1-v^0}{7-5v^0}, 1.5\frac{1-v^0}{1-2v^0}\right\} \tag{2}$$

Among them, v^0 represents the original Poisson's ratio of the material.

Taking the volume fraction of the pitch frame as the constraint condition, and the minimum flexibility as the optimization objective, after introducing the variable density model, the mathematical model of the topology optimization problem of the pitch frame can be obtained:

$$\begin{gathered}
\text{find}: \rho = \{\rho_1, \rho_1, \ldots \rho_1\}^T \in \Omega \\
\min: C(\rho_1) = F^T U = \sum_{i=1}^{N} \rho_i^p u_i^T k_0 u_i \\
s.t.: \sum_{i=1}^{N} \rho_i v_i - fV \leq 0 \\
F = KU \\
0 < \rho_{\min} \leq \rho_i \leq 1, i = 1, 2, \ldots N
\end{gathered} \tag{3}$$

In formula (3), Ω is the design space, F is the load array,U is the displacement array, u_i is the displacement vector of the element in the pitching frame, k_0 is the stiffness matrix when the element material density is equal to "1", v_i is the relative volume of the element, f is the volume fraction set in the constraint conditions, and V is the total volume of the pitching frame design space before optimization.

3.2. Multi-objective optimization model

The structure of the pitching frame needs to meet the load-bearing requirements under three typical working conditions, that is, the single box is placed in the center, the single box is placed on one side, and the two boxes are placed on both sides. Therefore, the optimization of the pitching frame belongs to the load multi-objective optimization problem. By weighting coefficient method, multi-objective optimization is transformed into single-objective optimization by giving weights to objective functions under different working conditions. The mathematical model of weighting coefficient method is as follows:

$$\begin{gathered}
\min \sum_{i=1}^{k} w_i f_i(x) \\
s.t. g_j(x) \leq 0 (j = 1, 2, \ldots, n) \\
w_i > 0 \sum_{i}^{k} w_i = 1
\end{gathered} \tag{4}$$

Where w_i is the weight coefficient of the ith objective function $f_i(x)$, and $g_j(x)$ is the j constraint condition.

3.3. Establishment of optimization model

Topology optimization of the pitch frame model [9], the largest contour entity of the pitch frame is used as the design space for topology optimization, as shown in Figure 5, the yellow area is the design space. Load is applied for three typical working conditions of single set of ammunition box placed in the center, single set of ammunition box placed on one side, and two sets of ammunition box placed on both sides.

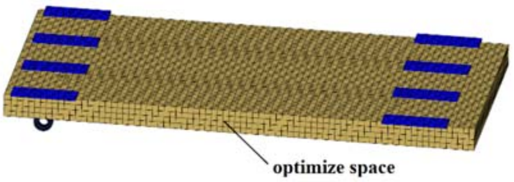


Figure 5. Schematic diagram of the design area of the pitch frame

The parameters of the pitching frame model are set as follows.

Design variable: material unit density in the design area of the pitching frame.

Constraints:

$$\frac{V_1}{V_\Omega} \le \frac{V_0}{V_\Omega} \tag{5}$$

Where V_0 and V_1 are the volumes of the three-dimensional model of the pitching frame before and after optimization respectively, and V_1 is the volume of the design area.

Objective: Minimize the weighted flexibility of the pitching frame structure under three working conditions.

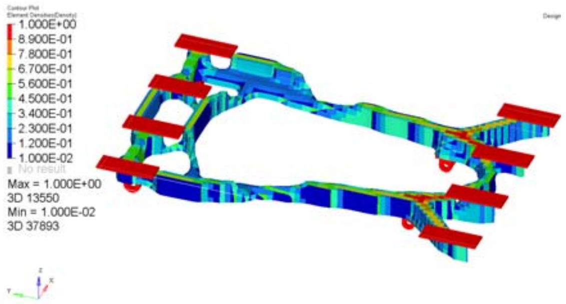


Figure 6. Topology optimization result of the pitch frame

After 52 optimization iterations, the topology optimization of the pitching frame is completed. Remove the elements with the material density below 0.2, and get the preliminary optimization model of the pitching frame, as shown in Figure 6. The element parts with retained materials constitute the main force transmission path of the pitching frame. Engineering the preliminary optimization model of the pitching frame, and modeling with standard I-steel profiles [10] to obtain the final 3D model of the pitching frame topology optimization, as shown in Figure 7. the mass of the optimized pitching structure is reduced by 19.6%.

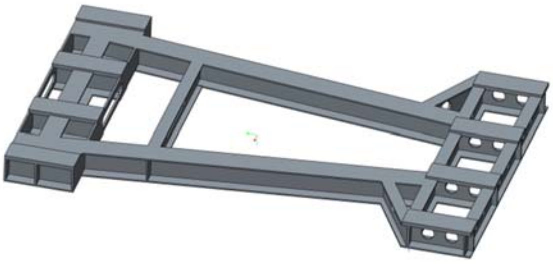
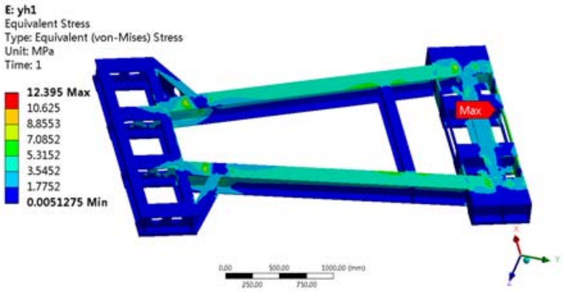


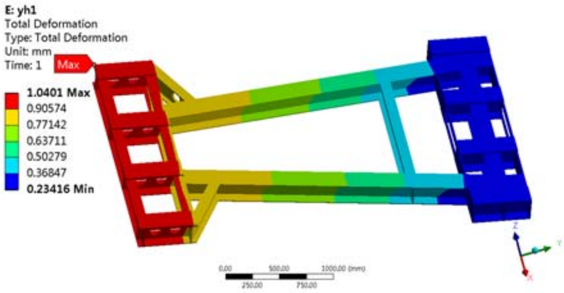
Figure 7. 3D model of the optimized pitch frame

4. VERIFICATION AND ANALYSIS OF OPTIMIZE MODEL MECHANICS

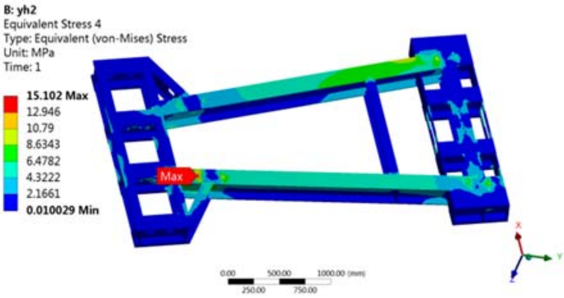
In view of three typical working conditions, that is, one set of bullet boxes is placed in the center, one set of bullet boxes is placed on one side, and two sets of bullet boxes are placed on both sides, the topology optimized model is analyzed by finite element method, and the optimized stress and displacement nephogram of the pitching frame is shown in Figure 8.



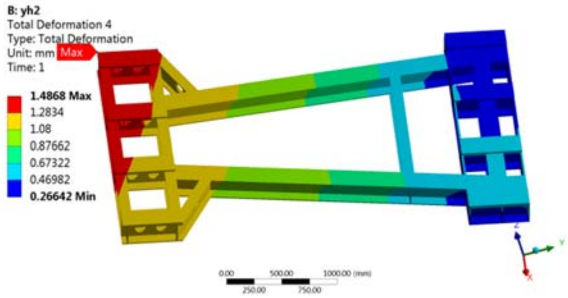
a) Stress of optimized pitching structure
(Working condition I)



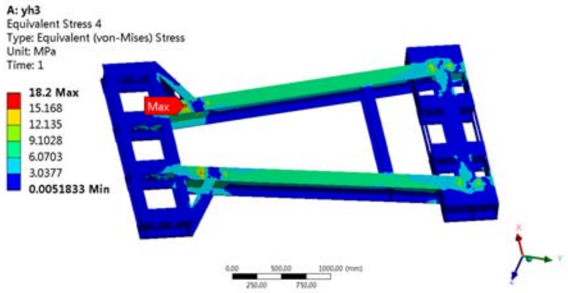
b) Displacement of optimized pitching structure
(Working condition I)



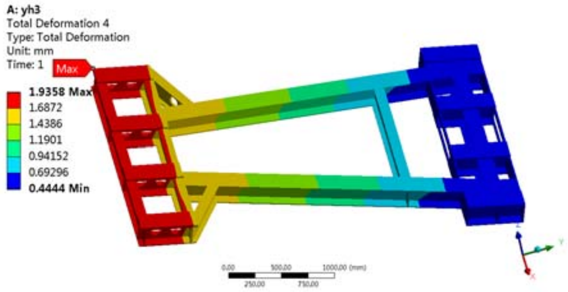
c) Stress of optimized pitching structure
(Working condition II)



d) Displacement of optimized pitching structure
(Working condition II)



e) Stress of optimized pitching structure
(Working condition III)



f) Displacement of optimized pitching structure
(Working condition III)

Figure 8. reprogram of stress and displacement of pitching frame under three typical working conditions

The stress-displacement results of the optimized pitch frame model are shown in Table 1. and are the maximum stress value and the maximum displacement value of the pitching frame before optimization, respectively; and are the maximum stress value and maximum displacement value of the optimized pitching frame respectively, and is the optimized amplitude value of the pitching frame respectively, and the calculation formula is as follows:

$$\Lambda_{\theta} = \frac{\theta_{\max}^{0} - \theta_{\max}^{1}}{\theta_{\max}^{0}} \qquad \theta=\sigma,\mathrm{u} \tag{6}$$

It can be seen from table 1 that under the condition of single box placed in the middle, the maximum stress value of the optimized pitching frame is reduced by 61.5% and the maximum displacement value is reduced by 42.9%; When the single box is placed on one side, the maximum stress of the optimized pitching frame is reduced by 57.2% and the maximum displacement is reduced by 23.2%; Under the condition of double-sided placement of double boxes, the maximum stress of theoptimized pitching frame is reduced by 60.3% and the maximum displacement is reduced by 23.9%. It shows that the stiffness and strength of the optimized pitching frame structure are effectively improved under three typical service conditions.

Table 1. Comparison of stress and displacement results of optimized pitching structure

Working condition	$\sigma^0_{\max}$	$\sigma^1_{\max}$	Λ_σ	$u^0_{\max}$	$u^1_{\max}$	Λ_u
Single box centered	32.19	12.40	61.5%	1.82	1.04	42.9%
Single box one side	35.26	15.10	57.2%	1.94	1.49	23.2%
Double box double sides	45.88	18.2	60.3%	2.55	1.94	23.9%

Remarks: the unit of stress is MPa; Displacement in mm

5. CONCLUSIONS

In this paper, the finite element method is used to analyze the stiffness and strength of the pitching frame structure of a missile launcher with three typical box bomb configurations. Aiming at the problem of local stress concentration caused by the heavy weight of the pitch frame structure and uneven stress distribution on the pitch frame, aiming at reducing the weight of the pitch frame and improving the stiffness and strength of the pitch frame, the multi-objective topology optimization and engineering design of the pitch frame are carried out. Through comparative analysis, it is shown that the topology optimization of the pitching frame improves the material utilization rate of the pitching frame, achieves a significant weight reduction, obtains a better force transmission path, and improves the overall stiffness and strength of the pitching frame.

REFERENCES

[1] Liu Hanchao, Wang Xuezhi, Li Min, et al. Topology optimization design of launcher bracket based on multi-body dynamics[J]. Journal of Ballistics, 2021, 33(1): 6.

[2] Xiang Gang. Analysis and optimization design of structural mechanical characteristics of a launching device[J]. Mine Warfare and Ship Protection, 2014(3):8.

[3] Diaz A R, Lipton R. Optimal material layout for 3D elastic structures. Structural Optimization, 1997, 13(1): 60-64.

[4] Rozvany G I N, Zhou M, Birker T. Generalized shape optimization without homogenization. Structural Optimization, 1992, 4(3-4): 250-252.

[5] Wang Y, Luo Z, Kang Z, et al. A multi-material level set-based topology and shape optimization method. Computer Methods in Applied Mechanics and Engineering, 2015,283: 1570-1586.

[6] Li Chao, Wang Xuezhi, Du Zhenyu, et al. Modal simulation analysis and optimization of missile carrier structure[J]. Journal of Projectiles, Rockets, Missiles and Guidance, 2018.

[7] Feng Wei. Research on box girder structure topology optimization based on variable density method[D]. North University of China, 2014.

[8] Jiachen Ouyang. Topology optimization design of functionally graded materials based on improved variable density method[D]. Huazhong University of Science and Technology, 2016.

[9] Lu Chunyan, Wan Changdong, Tian Fei. Optimal design of automobile brake caliper topology based on OptiStruct[J]. Mechanical Engineering and Automation, 2021(05): 71-73.

[10] Cheng Daxian. Mechanical Design Manual (Sixth Edition) [M]. Chemical Industry Publishing House. 2016.