According to the above analysis, the following conclusions were obtained:
1) Solid model has large scale and low efficiency, and it is not suitable for topology optimization design and analysis of complex structures;

2) Compared with the modal analysis results of the solid model, the error results of the three-layer plate model and the classical laminated plate model are relatively small, and the two modeling methods can well simulate the co-curing damping structure;

3) For the damping layer topology optimization problem, the three-layer plate model is more suitable because it needs to cut the embedded damping layer. To sum up, this paper chose the three-layer plate modeling method.

4. DAMPING LAYER OPTIMIZATION DESIGN STRATEGY

The damping layer optimization of viscoelastic co-curing structure has the characteristic of many design variables, large scale calculation, and etc. The design of damping layer was completed using topology optimization combined with size optimization strategy. The most commonly used sequential quadratic programming method (SQP) is used for size optimization, meanwhile, method of moving asymptotes (MMA) belongs to sequential convex programming method (SCP) is used to complete the damping layer topology optimization, which has good applicability to complicated topology [5,6].

Using moving asymptotes, MMA method transforms the implicit optimization problem into a series of explicit approximate sub-problems. In each iteration, gradient algorithm is used for solving convex approximation sub-problems to obtain new design variables.

For general structural topology optimization problems, the optimization model is shown as follows,

$$\begin{aligned} & find \quad x=\{x_1,x_2,\cdots,x_n\}^T \\ & \min \quad f_0(x) \\ & s.t. \quad f(x)\le 0, \qquad i=1,2,\cdots,m \\ & \qquad x_j^{\min}\le x_j\le x_j^{\max}, \quad j=1,2,\cdots,n \end{aligned} \tag{1}$$

Using MMA method to solve the problem in the formula (1), the artificial variables are introduced into the optimization model to improve each sub-problem. MMA expansion is used to approximate the optimal formulation, and to establish a series of convex linear separable sub optimization problems. The mathematical models of sub optimization problems are expressed as follows,

$$\begin{aligned} & \min \quad \tilde{f}_0(x)+a_0z+\sum_{i=1}^{m}\left(c_iy_i+\frac{1}{2}d_iy_i^2\right) \\ & s.t. \quad \tilde{f}_i(x)-a_iz-y_i\le 0, \quad i=1,2,\cdots,m \\ & \qquad \alpha_j^{\min}\le x_j\le \beta_j^{\max}, \quad j=1,2,\cdots,n \\ & \qquad z\ge 0, y_i\ge 0 \quad i=1,2,\cdots,m \end{aligned} \tag{2}$$

Z, a_i , c_i and $d_i\ge 0$ are given constants, and $c_i+d_i>0$. y_i is constructed as a fault design variable, then $\tilde{f}_i$ is the approximation form of the objective function and the constraint functions in the original mathematical model, which can be expressed as

$$\tilde{f}_i(x)=f_i^{(k)}(x^{(k)})+\sum_{j=1}^{n}p_{ij}^{(k)}\left(\frac{1}{U_j^{(k)}-x_j}-\frac{1}{U_j^{(k)}-x_j^{(k)}}\right)+\sum_{j=1}^{n}q_{ij}^{(k)}\left(\frac{1}{x_j-L_j^{(k)}}-\frac{1}{x_j^{(k)}-L_j^{(k)}}\right) \tag{3}$$

In the formula, $U_j^{(k)}$ and $L_j^{(k)}$ are used to adjust the convexity of the approximate function, and the iterative scheme in the MMA method is expressed as follows:

When $k=1,2$,

$$\begin{aligned} L_j^{(k)} &= x_j^{(k)}-0.5(x_j^{\max}-x_j^{\min}) \\ U_j^{(k)} &= x_j^{(k)}+0.5(x_j^{\max}-x_j^{\min}) \end{aligned} \tag{4}$$

When $k>=3$,

$$\begin{aligned} L_j^{(k)} &= x_j^{(k)}-r_j^{(k)}(x_j^{(k-1)}-L_j^{k-1}) \\ U_j^{(k)} &= x_j^{(k)}+r_j^{(k)}(U_j^{k-1}-x_j^{(k-1)}) \end{aligned} \tag{5}$$

In the formula，

$$r_j^{(k)}=\begin{cases}0.7 & (x_j^{(k)}-x_j^{(k-1)})(x_j^{(k-1)}-x_j^{(k-2)})<0 \\ 1.2 & (x_j^{(k)}-x_j^{(k-1)})(x_j^{(k-1)}-x_j^{(k-2)})>0 \\ 1 & (x_j^{(k)}-x_j^{(k-1)})(x_j^{(k-1)}-x_j^{(k-2)})=0\end{cases} \tag{6}$$

In the formula (2), $\alpha_j^{\min}$ 、 $\beta_j^{\max}$ are the moving limit parameters, and $U_j^{(k)}$ and $L_j^{(k)}$ should satisfy the following inequality,

$$L_j^{(k)}<\alpha_j^{\min}<x_j^{(k)}<\beta_j^{\max}<U_j^{(k)} \tag{7}$$

$p_{ij}^{(k)}$ and $q_{ij}^{(k)}$ are the first order expansion of the objective function and the constraint function for design variables at the design point $x_j^{(k)}$,

$$\begin{aligned} p_{ij}^{(k)} &= (U_j^{(k)}-x_j)^2\max(0,\frac{\partial f_i}{\partial x_j}(x^{(k)})) \\ q_{ij}^{(k)} &= (x_j-L_j^{(k)})^2\max(0,\frac{\partial f_i}{\partial x_j}(x^{(k)})) \end{aligned} \tag{8}$$

There is only one nonzero for a design variable $p_{ij}^{(k)}$ or $q_{ij}^{(k)}$ at the same time. This means that, for each design variable, there is only one asymptotic line at the same time for approximation. Therefore, whether the design function is monotonic or non-monotonic, the MMA method adopts the monotone approximation process.

Starting from the design point $x^{(k)}$, the optimization problem is solved by the dual method. Based on conjugate gradient algorithm, a series of equations are solved to obtain new design variables $x^{(k+1)}=x^*$. Then the next iteration starts, iterates until the original problem converges to the optimal solution.

5.DAMPING LAYER OPTIMIZATION DESIGN STRATEGY

In the development of a new weapon, a precision equipment is extremely sensitive to vibratioin environment. In order to meet the design requirements of lightweight and integration, the equipment bracket is made of viscoelastic co-curing structure. In this paper, taking the bracket as research objective, damping layer optimization design has been carried out.

5.1 Optimization design model

5.1.1 Topology optimization

The objective function of topology optimization is to make the maximum of the structural dynamic response minimum. Design variable is the unit density of each element of damping material, and the volume fraction of damping material is set as the constraint condition.

Optimization model is as bellowing:

$$\begin{aligned} & find: \rho_e \qquad e=1,\dots,N \\ & min：max（frfdis） \\ & s.t. \sum_{e=1}^{N}\rho_e v_e-\overline{v}\le 0 \end{aligned} \tag{9}$$

5.1.2 Size optimization

The objective function of topology optimization is to make the maximum of the structural dynamic response minimum. The thicknesses of each layers are taken as design variables, and the thickness of each layers should be constrained between requirement range.

Optimization model is as bellowing:

$$\begin{aligned} & find: h_i \qquad i=1,\dots,N \\ & min：max（frfdis） \end{aligned}$$

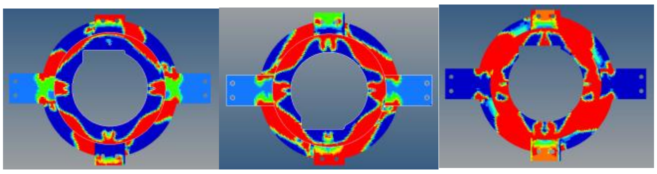
$$s.t. \sum_{i=1}^{N} h_i = H$$

$$a \leq h_i \leq b \qquad (10)$$

5.2 Optimization Results

5.2.1 Topology optimization

When the volume fraction is 0.4, 0.6 and 0.8, the topology optimization results of damping layer are shown in Figure 3, and the final damping layout of the bracket is determined as shown in figure 4.



a)0.4 b) 0.6 c) 0.8

Figure 3: *Topology optimization results*

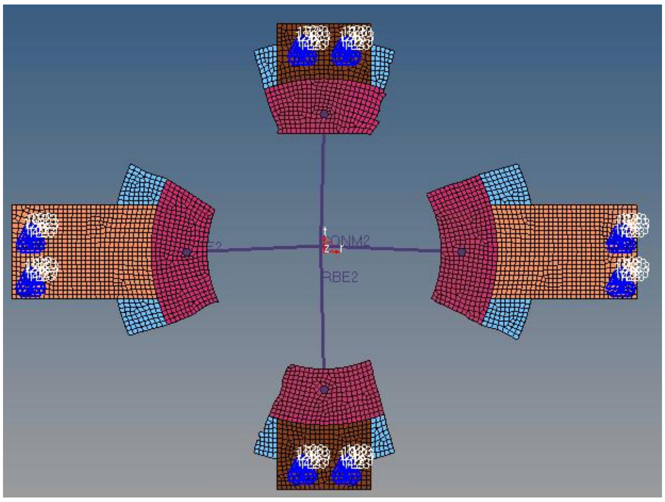


Figure 4: *Damping layout of bracket*

5.2.2 Size optimization

The convergence process of the objective function is shown in Figure 5, and Figure 6 shows the optimization results of design variables. After optimization, the results of objective function and constraint functions are shown in figure 7.

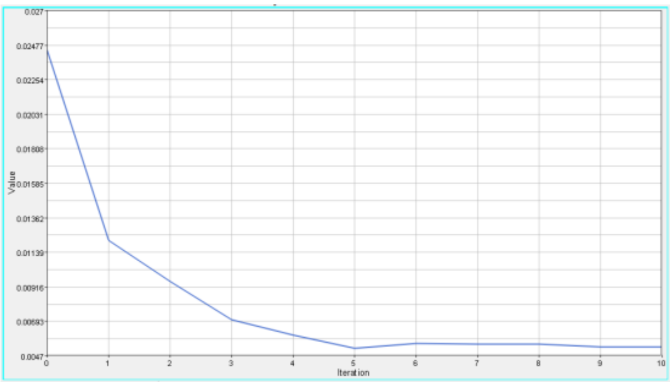


Figure 5: *Convergence process of objective function*

Design Variable ID	Design Variable Label	Lower Bound	Design Variable	Upper Bound
1	shell1	1.000E-02	3.197E+00	6.300E+00
2	shell2	1.000E-02	3.203E+00	6.300E+00
3	shell3	1.000E-02	3.185E+00	6.300E+00
4	shell4	1.000E-02	3.186E+00	6.300E+00
5	shell5	1.000E-02	1.407E+00	3.300E+00
6	shell6	1.000E-02	1.953E+00	3.300E+00
7	shell7	1.000E-02	2.898E+00	3.300E+00
8	shell8	1.000E-02	4.489E-01	3.300E+00
9	shell9	1.000E-02	8.243E-01	3.300E+00
10	shell10	1.000E-02	2.568E+00	3.300E+00
11	shell11	1.000E-02	3.059E+00	6.000E+00
12	shell12	1.000E-02	2.942E+00	6.000E+00
13	shell13	1.000E-02	1.235E+00	6.300E+00
14	shell14	1.000E-02	8.710E-01	6.300E+00
15	shell15	1.000E-02	8.759E-01	3.300E+00
16	shell16	1.000E-02	8.461E-01	3.300E+00
17	shell17	1.000E-02	8.768E-01	3.300E+00
18	shell18	1.000E-02	3.480E-01	6.000E+00

Figure 6: *Results of design variables*

RETAINED RESPONSES TABLE

Response User-ID	Type	Response Label	Subcase /RANDPS +Frqncy	Grid/ Element/ MID/PID/ Mode No.	DOF/ Comp /Reg	Response Value		Objective Reference/ Constraint Bound	Viol. %
7	FRDSP	frf	1 686.0	7696	M-TZ	5.326E-03	MIN		
1	EQATN	deq1	--	--	--	6.400E+00	>	6.200E+00	0.0
1	EQATN	deq1	--	--	--	6.400E+00	<	6.400E+00	0.0 A
2	EQATN	deq2	--	--	--	6.371E+00	>	6.200E+00	0.0
2	EQATN	deq2	--	--	--	6.371E+00	<	6.400E+00	0.0 A
3	EQATN	deq3	--	--	--	3.360E+00	>	3.200E+00	0.0
3	EQATN	deq3	--	--	--	3.360E+00	<	3.400E+00	0.0
4	EQATN	deq4	--	--	--	3.347E+00	>	3.200E+00	0.0
4	EQATN	deq4	--	--	--	3.347E+00	<	3.400E+00	0.0
5	EQATN	deq5	--	--	--	3.392E+00	>	3.200E+00	0.0
5	EQATN	deq5	--	--	--	3.392E+00	<	3.400E+00	0.0 A
6	EQATN	deq6	--	--	--	6.001E+00	>	5.900E+00	0.0
6	EQATN	deq6	--	--	--	6.001E+00	<	6.100E+00	0.0

Figure 7: *Results of objective function and constraint functions*

It can be seen that the peak value of the structural vibration response is reduced from 2.44964E-02 to 5.32610E-03 after the optimization, and the damping target of the co-curing damping structure is realized.

6 CONCLUSION

In this paper, the finite element model of the co-curing structure was established by the three-layer plate modeling method, and damping layer optimization was completed using topology optimization combined with size optimization strategy. The research lays the foundation for engineering application of viscoelastic co-curing structure, and has a wide application prospect in aerospace and other high-tech fields.

REFERENCES

[1] Wang, C., Xu, CH. 2002. Study on vibration suppress of a cabin structure based on dynamic testing. Journal of Mechanical Strength, 24 (1), 49-51.

[2] Shen, CH., Liang, L. 2006. Vibration suppression of a payload racket in a satellite. Journal of Astronautics, 27 (3), 503-506.

[3] Shaohui, Z., Hongyou, C., Haiquan, M., Zhiying, Q. 2011. Progress and perspect on viscoelastic damping technology for spacecraft application. Spacecraft Engineering, 20 (1), 120-128.

[4] Qi-yong, Y., Yu-pu, M., Wan-tao, G., Yi-bo, W. 2007. Structural damping composite and its research progress. Materials Engineering, 2 (1), 253-258.

[5] Svanberg, K. 1987. The method of moving asymptotes- a new method for structural optimization. International Journal of Numerical Methods in Engineering, 12 (1), 359-373.

[6] Svanberg, K. 2002. A class of globally convergent optimization methods based on conservative convex separable approximations. SLAM Journal of Optimization, 12 (2), 555-573.