Stiffness Enhancement Method for Complex Thin-walled Parts Driven by the Principal Stress Field

Weinan Zhang, Ning Dai*, Ce Guo, Yi YU and Sai Gong

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, JiangSu, 210016, China
*e-mail: dai_ning@nuaa.edu.cn

Abstract. Aiming at the problem that the stiffness enhancement effect of traditional reinforcing methods such as Tic-tac-toe type stiffener is not always optimal in the face of complex thin-walled parts, a stiffness enhancement method for complex thin-walled parts is proposed. In this paper, the bionic principle of Victoria vein layout based on the principal stress field model is explored, and an optimization method for the lightweight stiffness enhancement of complex thin-walled parts driven by the principal stress field is proposed. The experimental results show that the specific stiffness of the complex thin-walled parts generated by this method increases by 28% when the quality of the structure is basically the same as that of the traditional Tic-tac-toe type stiffeners.

1. Introduction

With the rapid development of aerospace technology, there is a growing demand for structural lightweight, especially for reducing weight and ensuring that the stiffness of the structure meets the requirements. For large-sized thin-walled parts such as missile cabin, not only high structural integrity is preserved, but also a large amount of space is reserved for placing other objects in the cabin, with high bearing efficiency [1]. However, when the structure has a large thickness and is very thin, the stiffness will also weaken [2]. Especially in the face of complex working conditions, there is still room for further optimization of the strengthening effect of traditional Tic-tac-toe type reinforcement in complex thin-walled parts. Therefore, we need a new method to enhance the stiffness of such complex thin-walled parts in the cabin.

The complex thin-walled structure stiffness enhancement method basically has two kinds: one kind is to use high stiffness of the material, one kind is through the structure design, the layout of the rational allocation of materials, such as the topology optimization and near surface reinforcement method [2-3], topology optimization, including variable thickness method [4-5], the variable density method [6] and microstructure of equivalent homogenization method [7], etc. This paper mainly discusses how to achieve high specific stiffness through structural design.

Near-surface reinforcement method is a widely used method in engineering for the design of lightweight and high rigidity. In the past, reinforcement arrangement was mainly based on the experience of engineers [3], and "borehole type" and "meter type" are relatively common, lacking relevant theoretical basis. However, organisms in the natural environment have developed the optimal structure that can adapt to the harsh environment after a long process of evolution. Zhang et al. [8] proposed a design method that uses biological bifurcations to optimize the topology of the stiffeners of the frame structure so as to improve the specific stiffness. Li et al. [2] proposed a calculation framework based on the principal stress line to design and optimize the rib layout on any shell, so as to improve the...
overall structural stiffness and mechanical properties. However, this method is more from the perspective of computer graphics. TAM et al. [9] proposed a stiffness enhancement method for additive manufacturing along the principal stress line, and involved the problem of selecting the principal stress line according to manufacturing constraints and other factors.

Therefore, this article from the perspective of bionics, Victoria veins distribution, put forward the equivalent line of principal stress calculation model and solving the lines reflect the overall density of the principal stress, equivalent principal stress along the lines of the complex thin-walled parts near surface stiffener layout and optimization, and through the finite element analysis and physical test, verify the effectiveness of the proposed method.

2. Methods

2.1. Research on bionic theory of high rigid structure
Organisms in nature have evolved over eons of time, organisms in nature have grown into optimal structures suitable for harsh environments. As for the stiffness enhancement of thin-walled structures, this paper selected Victoria as the research object through previous investigations[10]. By observing the distribution of veins at the bottom of Victoria leaf, the organisms in nature have been modelled. Water pressure and its own gravity, common in nature, were applied, and fixed support was applied at the root of the center of the leaf. The stress field was analysed to simulate the loading of Victoria leaf in nature, and the results were shown in Figure 1.

![3d model](image1)

(a) 3d model

![The locus of the principal stress field](image2)

(b) The locus of the principal stress field

![Enlarge figure](image3)

(c) Enlarge figure

Figure 1. The connection between the venation of Victoria and the principal stress field.

Through observation, it can be found that the distribution of Victoria's tendons in the circumferential direction is consistent with the distribution of the central tensile stress in the main stress field. In the radial direction, the first stage tendons start from the central support and diverge in all directions, which is consistent with the radial compressive stress distribution in the main stress field. The track of the maximum principal stress indicates the path of the load transferred by the vein. Therefore, inspired by this, the main idea of this paper is to enhance the structural stiffness by arranging reinforcing bars along the main stress line near the surface of the shell.

2.2. Extraction of equivalent principal stress lines and 3D modeling
There have been many researches on the generation mode of the principal stress line, and the generation mode of different industries is also different [11]. The method in this paper is firstly given a complex thin-walled structure, and then finite element analysis is carried out by applying loads and constraints to generate the main stress field. At the same time, the stress data generated by the main stress field in the design domain is obtained, and the stress information at the nodes is extracted and stored. The family of principal stress lines is generated based on node stress information. Along the line of principal stress of each principal stress line stiffener layout is apparently not reality, so this article need to improve overall stiffness in the principal stress line family of principal stress line
extraction, based on the theory of tensor topology in the degradation area boundary and the dense regions of "advantage principal stress line" the two special cases, extraction principle is as follows:

Figure 2. The generation pipeline of high specific stiffness.

Step1. Import the principal stress line, and calculate every principal stress contour of maximum curvature kmax, will kmax between kmax + Δk together as one family with one assignment.

Step2. Use function to solve the distance calculation on 3dmax every race of two principal stress boundary line of maximum point to point distance di and principal stress line number mi, linear density values for each group principal stress di/mi, curve was generated by size order PCi ∈ {PC0, PC1, PCi}.

Step3. Find out the maximum point-to-point distance between the initial principal stress line CURSi and the next principal stress line CURj of each group. Remove the redundant principal stress line if it does not meet the requirements, + is determined by the overall weight of the structure.

2.3. Optimization of near surface reinforcement for high stiffness structures

In this paper, three parameter values affecting the maximum deformation D are extracted and parameterized: shell thickness DS_T, stiffener width DS_W and stiffener height DS_H. In consideration of surface curvature and actual working conditions, a reasonable variable value range is set to continue the dimensional optimization analysis. After the optimal solution is obtained, the size is applied to the structural design. The influence of three parameters on the maximum deformation D is shown in Figure 3.

\[
\begin{align*}
\text{min} & \ = D \\
\text{s.t.} \quad & -\sigma_t \leq \sigma \leq \sigma_t \\
D & = f(DS_T, DS_W, DS_H)
\end{align*}
\]

Figure 3. The response surface of three sets of parameters to the maximum deformation.
By analysing the response surface between the variable and the response value, the influence rule of size parameters on the maximum deformation in the design of high rigid thin-wall structure is systematically analysed. These trends indicate that there is an interaction between the three variables, and the optimal solution exists for maintaining the mass within a certain range while obtaining the minimum deformation. The optimal solution: DS_W is 1.73mm, DS_H is 2.46mm, DS_T is 1.97mm, and the maximum deformation and mass are 0.08mm and 0.52kg respectively.

3. Experimental verification and analysis

3.1. Stiffness evaluation standard

For the stiffness evaluation criteria of special-shaped shell structure, an index called efficiency of specific stiffness structure is introduced after considering the factors such as stiffness, material and structure quality comprehensively [9]. The higher this value is, the higher the stiffness of the structure will be. The concrete definition is shown in formula 4, where E represents young's modulus, represents the maximum deformation of the structure, and M represents the mass of the structure.

\[
\delta = \frac{E}{\varepsilon m}
\]  

(4)

3.2. Finite element analysis

In the process of finite element analysis, the control group chose to use the traditional wellbore reinforcement model, while the experimental group chose to use the PSL reinforcement model along the main stress line and the optimized size model. The data in Section 2.3 was selected as the size of the optimization group. The weights of the three groups were kept basically the same. The same material was used, the same boundary conditions and loads were added, and the same grid was divided to carry out the comparative test.

Among them, the specific stiffness of PSL structure is 20% higher than that of the well-shaped structure, and the optimized structure is 40.9% higher than that of the traditional well-shaped structure. In addition, the total strain energy of the optimized structure [12] decreases to different degrees compared with the other two structures, which proves the feasibility of the method from the side.
Table 1. Experimental parameters of each model

| Type               | Mass  | The biggest deformation | The total strain energy | Specific stiffness |
|--------------------|-------|-------------------------|-------------------------|-------------------|
| Tic-tac-toe type   | 0.538 | 0.123                   | 523.670                 | 15.11             |
| structure          |       |                         |                         |                   |
| PSL structure      | 0.516 | 0.106                   | 493.840                 | 18.28             |
| Optimized structure| 0.516 | 0.091                   | 427.850                 | 21.30             |

3.3. Physical compression test

The three models were printed by the light curing technology, (a) adding traditional Tic-tac-toe type reinforcing rib to the model, (b) adding master stress line reinforcing rib to the model, and (c) adding optimized master stress line reinforcing rib to the model. Label the three models and carry out compression tests, as shown in figure 6. Due to the outer surface of the workpiece add aerodynamic load for special-shaped structure, by means of mechanical pressure on aerodynamic load is very difficult, special-shaped structure add and add the uniformly distributed load by means of hydraulic or pneumatic, need the workpiece sealing up and down, change the characteristics of the special-shaped structure itself, lost the significance of research, so we use the equivalent of the simplified load.

(a) Tic-tac-toe type  
(b) PSL type  
(c) Optimized type

Figure 6. Label the workpiece and perform compression test

The relevant data after the workpiece is compressed is shown in figure 7, where the Tic-tac-toe type shape structure of the reference group appears obvious unloading phenomenon when the maximum load is 800N and the displacement is 8.5mm, and the compression stiffness [13] is 94N/mm. When the maximum load of PSL model is 870N, the displacement is 7.7mm, the maximum load capacity is 870N, and the compression stiffness is 112N/mm. When the maximum load of the optimization model is 910N, the displacement is 7.6mm, the maximum load capacity is 900N, and the compression stiffness is 120N/mm.

![Load-Displacement Diagram](image)

Figure 7. Displacement-load diagrams for the three structures.
4. Conclusion

As a comparative test, the compression stiffness of the optimized model is increased by 7% compared with that of the PSL reinforced reinforcement model and 28% compared with that of the traditional Tic-tac-toe type reinforcement model, reflecting the enhanced stiffness of some parts of the structure. In summary, the physical test results show that the specific stiffness of the optimized model is 28% higher than that of the traditional Tic-tac-toe type model, which is basically the same as the results of the finite element analysis. The results show that the high rigidity bionic model designed by this method has a significant effect on the specific stiffness improvement.

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