ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

# RESEARCH ON STRUCTURAL DESIGN OF TAIL BOOM FOR AN UNMANNED HELICOPTER

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## Abstract

The structural design of metallic tail boom for an unmanned helicopter which possesses a single rotor and tail-rotor is developed. For the sake of promoting the development of lightweight and efficient tail boom structure under the booming new manufacturing technology, the concept of sub-strengthening frame is proposed. Subsequently the structural design of two kinds of tail booms with conventional monocoque structure and sub-strengthening frame is implemented under the constant weight condition. Linear buckling analysis and strength analysis are developed under yawing condition. The analysis demonstrates that the introduction of sub-strengthening to the conventional monocoque tail boom structure significantly improves the tail boom's buckling load by 9.2%. Based on works above, a sizing optimization model of sub-strengthening frame tail boom structure is constructed for weight reduction. And it deserves further attention for helicopter design industry which endeavors to develop high performance lightweight tail boom structures with new manufacture technology. The results manifest that the optimized tail boom not only meets the requirements of structural design, but also reduces the structural weight by 7.4%, the structural configuration design of metallic tail boom is reasonable and feasible.

**Keywords:** tail boom of unmanned helicopter, structural design, sub-strengthening frame, buckling characteristics

## 1. Introduction

Metallic monocoque tail boom possesses large bending-torsion rigidity and it facilitates the manufacture, is commonly applied to the design of light helicopter. At present, structural design of monocoque tail boom is usually conservative in order to ensure that the structure is secure, which limits the development of lightweight structures. With the development of new manufacturing technology, scholars in both domestic and abroad have conducted some study on new structural forms. Mehnen [1] investigated the process capabilities of fabricating complicated geometries using WAAM, and subsequently analyzed the thermo-mechanical behaviour of the multi-layer wall structure [2]. Murphy [3] put forward the concept of sub-stiffened panel and believes that the sub-stiffened panel may improve the structural efficiency of panel. Quinn [4] verified the improvement of stability performance under uniaxial loading and pointed out that the critical buckling load of the plate is improved with the introduction of sub-stiffening to the traditional stiffened panel. Yan ZH [5] proposed a two-scale topology optimization method to design the innovative grid-stiffened pattern for maximizing the critical buckling load of thin-walled cylindrical shells. Song-ze L [6] pointed out that the aspect ratio of sub-stiffened panel must be within a certain range in order to ensure it acquires preferable structural stability. Bo W [7] proposed an innovative hierarchical stiffening panel and indicated that the initial imperfection sensitivity has the smaller effect on the critical buckling load of sub-stiffened panel compared to the traditional stiffened panel.

At present, there are few reports about the research on structural design of tail booms with sub-strengthening frame domestic and abroad. Therefore, the structural design of tail boom for an unmanned helicopter which possesses a single rotor and tail-rotor is developed. First of all, the optimal load-carrying path of tail boom structure is obtained on the basis of topology optimization and structural layout is rapidly determined. Secondly, the concept of sub-strengthening frame is proposed, subsequently the structural design of two kinds of tail booms with conventional monocoque structure and sub-strengthening frame is implemented under the constant weight condition. Linear buckling analysis and strength analysis are developed under yawing condition. Based on works above, a sizing optimization model of sub-strengthening frame tail boom is constructed for weight reduction and to determine the ultimate parameters of tail boom structure.

## 2. Structural Design of Monocoque Tail Boom

### 2.1 Structural Design of Monocoque Tail Boom

Structural design of tail boom is conducted on the basis of the theory of structures. Tail boom is composed of skin and frame and they are both constructed from AL2024-T351. As for the mechanical properties of it, $E$ = 73.774 Gpa, $u$ = 0.33, $\rho$ = 2780 kg/m$^3$ and $\sigma_s$ = 325 MPa. Flight loads of unmanned helicopter in yawing state are selected as severe loads condition and the safety factor $f$ = 1.5.

In order to determine the layout of skin and frame rapidly, a topology optimization model of tail boom structure is constructed based on variable density method by using FEM software of HyperWorks [8], and topology optimization model is as shown in Figure 1. Topology optimization aims at minimizing the structure volume, takes the element density as the design variable, and displacement of tail boom is set as the constraint. With regard to the finite element model, the tail boom structure is simulated with QUAD4 element, fixed constraints ($UX$ = 0, $UY$ = 0, $UZ$ = 0, $RX$ = 0, $RY$ = 0, $RZ$ = 0) are applied at the root of tail boom structure, and the yawing loads are imposed on structural nodes by using RBE3 for calculation. The objective function converges after 15 iterations and the optimized structure topology is as shown in Figure 2.

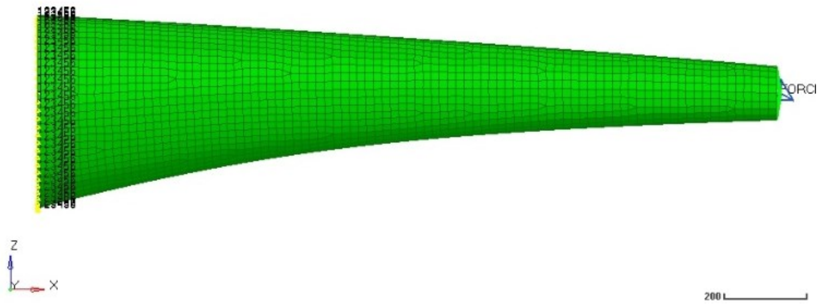

Figure 1 –Topology optimization model.

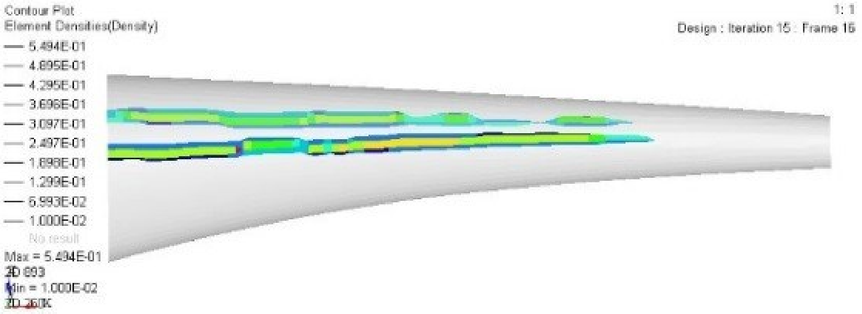

Figure 2 – The optimized result.

There are merely high-efficiency load carrying elements left in the design property. The density contour indicates that thicker skin should be arranged on the left side (compression-side) of the tail boom structure, and the spacing between the frames in the front of tail boom should be smaller than that in the rear of tail boom. Combined with the theory of aircraft structural design, structural layout and the parameters of component are determined, and the structural layout of the tail boom is as shown in Figure 3. The thickness of skin on the left side equals to 1.1 mm and the thickness of skin on the right side equals to 0.9 mm. Frame 1 and frame 2 with the cross section of “I” shaped and frame 3 with the cross section of “C” shaped are arranged at tail boom along the heading. The parameters of frames are shown in Table 1.

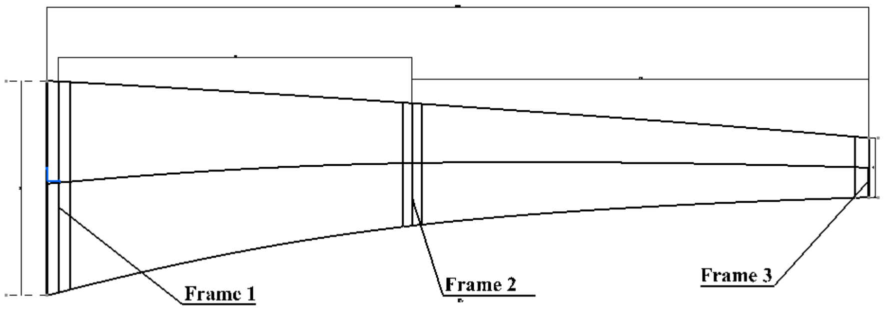

Figure 3 – Structural layout of the tail boom.

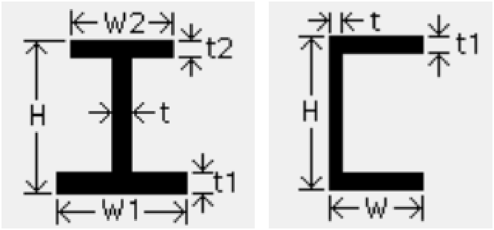

Figure 4 – Cross-section of Frames.

Table 1. Parameters of frames

| Frame | W1 (mm) | W2 (mm) | H (mm) | t1 (mm) | t2 (mm) | t (mm) |
|---|---|---|---|---|---|---|
| 1 | 50 | 50 | 60 | 2 | 2 | 1.2 |
| 2 | 50 | 50 | 60 | 2 | 2 | 1.2 |

| Frame | W (mm) | H (mm) | t1 (mm) | t (mm) |
|---|---|---|---|---|
| 3 | 40 | 30 | 2 | 1.2 |

## 2.2 Buckling Analysis of Tail Boom Structure under Yawing Condition

MSC. Patran/Nastran is used to construct the finite element model of tail boom. With regards to the finite element model, skin and web of frame are simulated with QUAD4 element, and the BEAM2 element is used to establish the edge of frame [9]. Fixed constraints (*UX*=0, *UY*=0, *UZ*=0, *RX*=0, *RY*=0, *RZ*=0) are applied at the root of tail boom structure and the yawing loads are imposed on structural nodes by using RBE3 for calculation.

Linear buckling mode of tail boom is as shown in Figure 5. As for the first order buckling mode [10], the frames don’t lose stability and the vulnerable-area located in the right skin which is between the frame 1 and frame 2. The eigenvalue of the first order mode equals to -1.4795, which indicates that the tail boom meets the requirement of stability design.

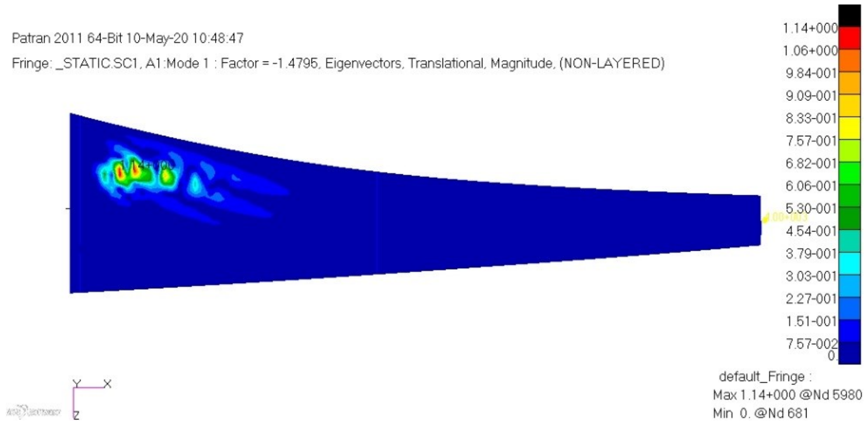

Figure 5 –The first order mode of tail boom.

## 2.3 Static Strength Analysis under Yawing Condition

Stress contour and displacement contour of tail boom structure are as shown in Figure 6 and Figure 7 respectively.

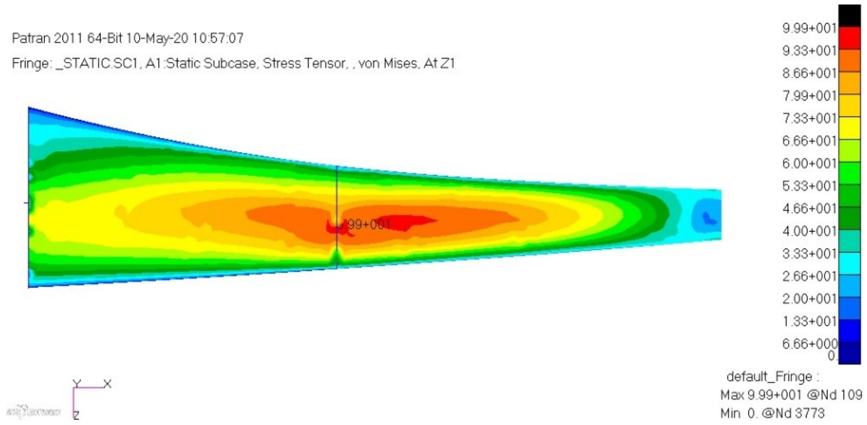

Figure 6 – Stress contour of structure.

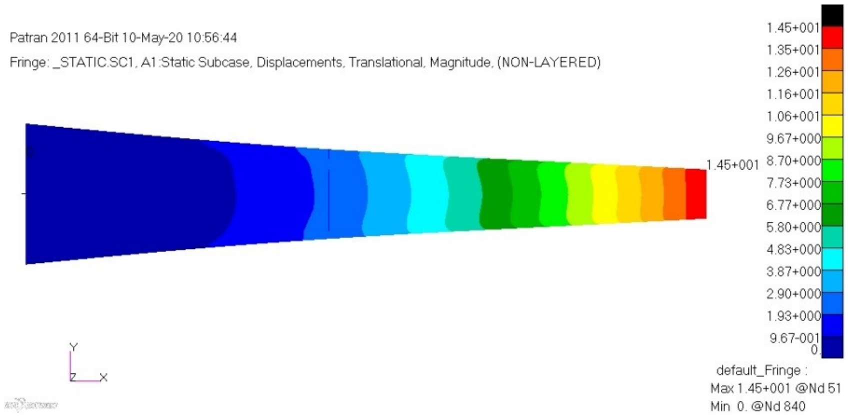

Figure 7 – Displacement contour of structure.

Maximum stress equals to 99.9 MPa and it is located in the right skin that is near frame 1, which is smaller than the failure stress of material. Maximum displacement situates in the end of tail boom structure with value of 14.5 mm, which meets the requirement of stiffness design. The analysis demonstrates that the tail boom meets the requirements of structural design and the mass of it equals to 5.133 kg.

## 3. Structural Design of Sub-strengthening Frame Tail Boom

### 3.1 Concept of Sub-strengthening Frame

The concept of sub-strengthening frame is proposed contrapose to the structural design of metallic tail boom for an unmanned helicopter. The difference between the sub-strengthening frame and strengthening frame is that the thickness and width of edge, thickness and height of web of sub-strengthening frame are usually smaller than that of strengthening frame. Similarly, bending rigidity of sub-strengthening frame is usually smaller than that of strengthening frame. Sub-strengthening frame possesses the capacity to improve the bending rigidity of the monocoque tail boom structure and plays a role in improving the structural stability of monocoque tail boom as it is an auxiliary load-bearing structure.

### 3.2 Structural Design of Sub-strengthening Frame Tail Boom

The conventional monocoque tail boom structure described in 2 is referred to as the basic structure for convenience of expression. Structural design of sub-strengthening frame tail boom is implemented under the condition that possesses constant weight with the basic structure. Based on the structural design of monocoque tail boom, the existing frames are set as the strengthening frames and are maintained invariant. The thicknesses of the skin are reduced and sub-strengthening frames are designed so as to investigate the effects that the introduction of sub-strengthening frames to tail boom structure on the structural performance of it. Two sub-strengthening frames namely frame A and frame B respectively are evenly arranged between frame 1 and frame 2 and two sub-strengthening frames namely frame C and frame D respectively are evenly arranged between frame 2 and frame 3. The cross-section of sub-strengthening frame is “I” shaped and parameters of them are as shown in Table 2.

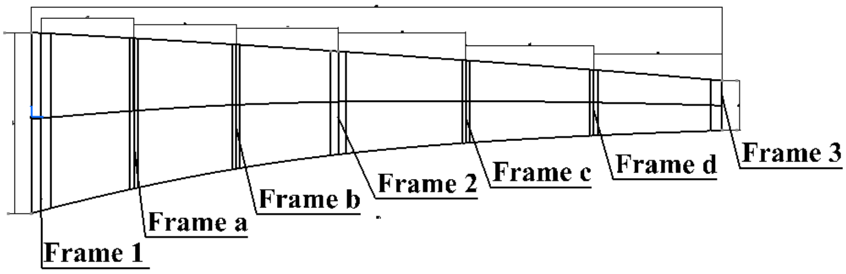

Figure 8 – Structural layout of the tail boom.

Table 2. Parameters of Sub-strengthening Frames

| Sub-Frame | W1 (mm) | W2 (mm) | H (mm) | t1 (mm) | t2 (mm) | t (mm) |
|---|---|---|---|---|---|---|
| A | 30 | 30 | 40 | 1.4 | 1.4 | 0.8 |
| B | 30 | 30 | 40 | 1.4 | 1.4 | 0.8 |
| C | 30 | 30 | 40 | 1.4 | 1.4 | 0.8 |
| D | 30 | 30 | 30 | 1.4 | 1.4 | 0.8 |

### 3.3 Buckling Analysis of Sub-strengthening Frame Tail Boom

Linear buckling mode of sub-strengthening frame tail boom is as shown in Figure 9. As for the first order buckling mode, the vulnerable-area located in the right skin and the outer displacement is limited to the region between frame 1 and sub-strengthening frame A. Eigenvalue of the first order buckling mode is equal to -1.6159, which indicates that the sub-strengthening frame tail boom meets the requirement of stability design. Bending rigidity of tail boom structure is improved on account of the introduction of sub-strengthening frame and thus the vulnerable-area of skin is reduced.

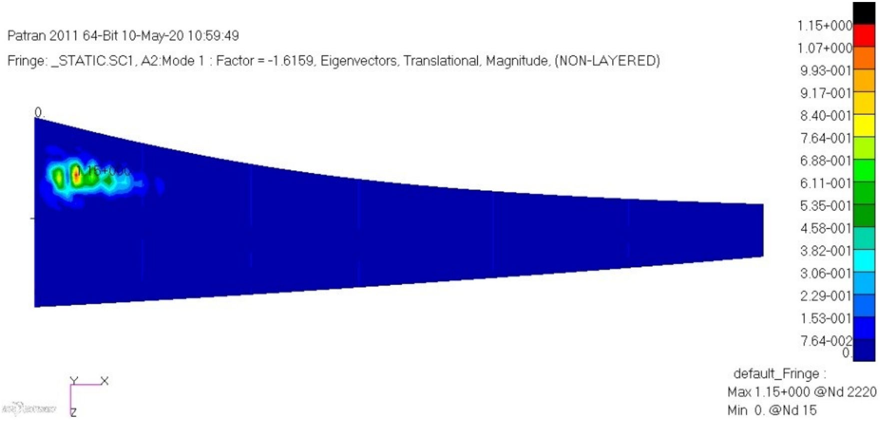

Figure 9 – The first order mode of sub-strengthening frame tail boom.

## 3.4 Static Strength Analysis under Yawing Condition

Stress contour and displacement contour of tail boom structure are as shown in Figure 10 and Figure 11 respectively.

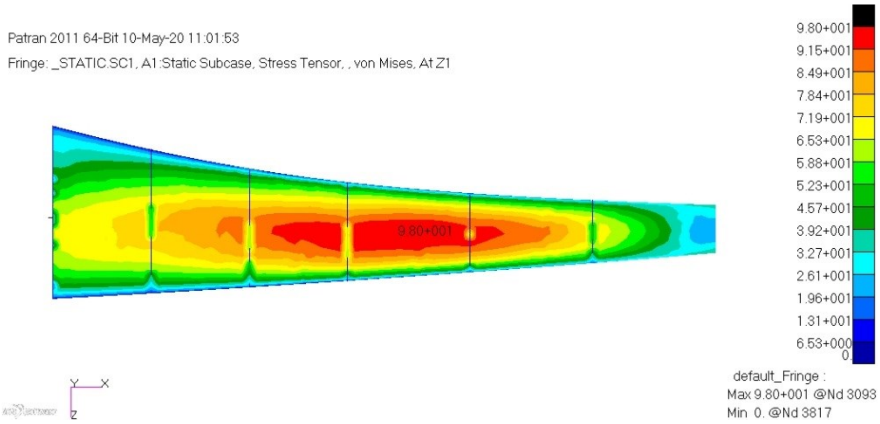

Figure 10 – Stress contour of structure.

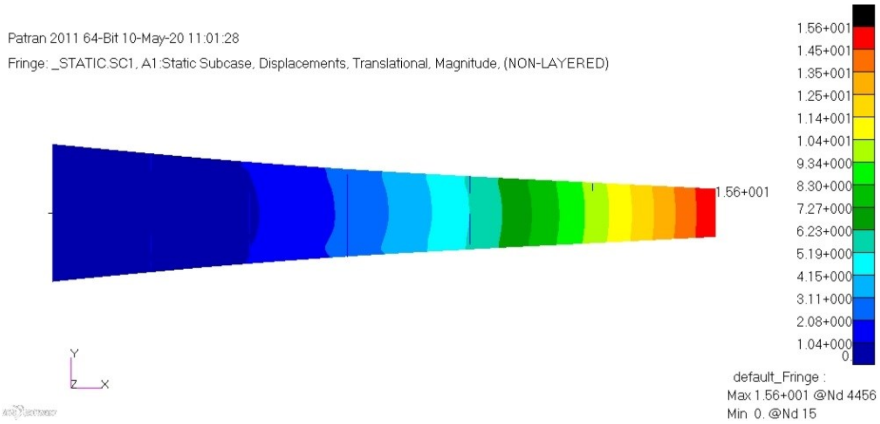

Figure 11 – Displacement contour of structure.

The results indicate that the maximum stress is located in the right skin that between the frame 1 and sub-strengthening frame C. Maximum stress of structure equals to 98 MPa, which is smaller than the failure stress of material. The maximum displacement situates in the end of tail boom structure, with value of 15.6 mm, which meets the requirement of stiffness design.

The analysis demonstrates that the introduction of sub-strengthening to the conventional monocoque tail boom structure significantly improves the tail boom's buckling load by 9.2%. Maximum stress of sub-strengthening frame tail boom declines 1.9% compared with the basic structure. Although the maximum displacement increases 7% compared with the basic structure, which still meets the requirement of stiffness design. The introduction of sub-strengthening frame to the conventional monocoque tail boom structure makes it gain a significant improvement in structural stability, and the comprehensive performance of sub-strengthening frame tail boom is superior to the basic structure. It can be considered that a reasonable material distribution between the skin and the frame under the constant weight condition is acquired, which makes the tail boom structure gain higher critical buckling load under the premise that the maximum stress is smaller the failure stress of material.

## 4. Sizing Optimization for Sub-strengthening Frame Tail Boom

Based on the results of 3.3 and 3.4, it can be concluded that the stress level of sub-strengthening frame tail boom structure is low. The tail boom structure possesses much residual intensity, therefore, which can be further optimized for weight reduction.

### 4.1 Sizing Optimization for Structure

Hyperworks is applied to conduct the sizing optimization model for sub-strengthening frame tail boom structure [11]. According to 3.3, the region lack of stability of skin is between frame 1 and sub-strengthening frame A, hence the optimization is arranged at the region between the frame 1 and frame 2. Sizing optimization is aims at minimizing the mass of structure. Thicknesses of skin, thicknesses of web and thicknesses of edge in design property are set as design variables and count up to 23. Displacement and stress of tail boom structure are set as constraints. Sizing optimization model is as shown in Figure 12 and the constraints are as shown in Table 3.

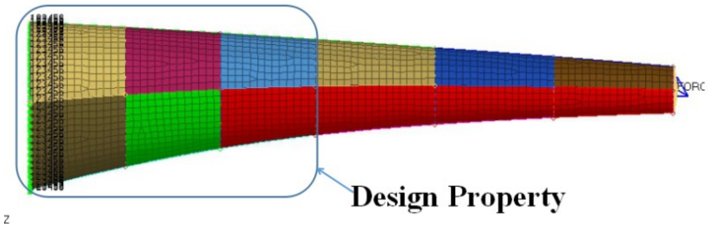

Figure 12 – Design property.

Table 3 – Constraints

| constraints | value |
|---|---|
| maximum stress (MPa) | ≤325 |
| maximum displacement (mm) | ≤20 |
| Thickness of skin (mm) | 0.6~1.8 |
| Thickness of web of frame (mm) | 0.6~2 |
| Thickness of edge of frame (mm) | 0.8~3 |
| Thickness of web of sub-frame (mm) | 0.5~1.2 |
| Thickness of edge of sub-frame (mm) | 0.5~1.6 |

Sizing optimization problem for tail boom structure can be expressed by the mathematical model as follows:

$$\text{Find } X = \{X_1, X_2, \ldots, X_{23}\} \tag{1}$$

$$Min = M \tag{2}$$

$$s.t = \begin{matrix}\sigma\le[\sigma_i] \\ \delta\le[\delta_i]\end{matrix} \tag{3}$$

Among which, $X_1$, $X_2$…, and $X_{23}$ are constraints of tail boom structure and M is the mass of tail boom. $[\sigma_i]$ is the allowable stress of structure while $[\delta_i]$ is the allowable displacement of tail boom structure [12].

The objective function converges after 4 iterations. The optimized results of design variables and the variation tendency of some design variables are as shown in Figure 13 and Figure 14 respectively. Thicknesses of strengthening frames and sub-strengthening frames are shown in Table 4.

Table 4. Parameters of Frames

| Frame | W1 (mm) | W2 (mm) | H (mm) | t1 (mm) | t2 (mm) | t (mm) |
|---|---|---|---|---|---|---|
| 1 | 50 | 50 | 60 | 0.84 | 0.7 | 0.7 |
| 2 | 50 | 50 | 60 | 0.84 | 0.7 | 0.7 |
| Frame | W (mm) | H (mm) | t1 (mm) | t (mm) | | |
| 3 | 40 | 30 | 2 | 1.2 | | |
| Sub-Frame | W1 (mm) | W2 (mm) | H (mm) | t1 (mm) | t2 (mm) | t (mm) |
| A | 30 | 30 | 40 | 0.7 | 0.7 | 0.7 |
| B | 30 | 30 | 40 | 0.7 | 0.7 | 0.7 |
| C | 30 | 30 | 40 | 1.4 | 1.4 | 0.8 |
| D | 30 | 30 | 30 | 1.4 | 1.4 | 0.8 |

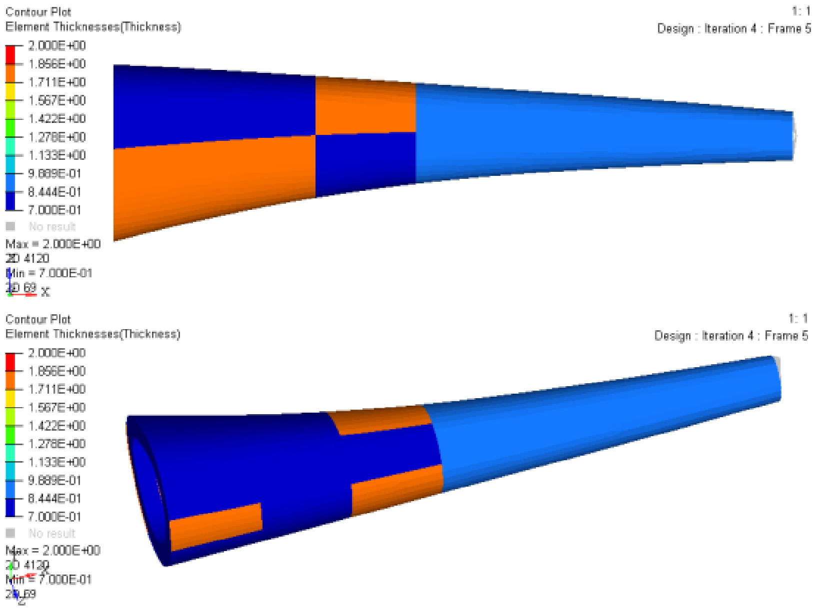

Figure 13 – The optimized results.

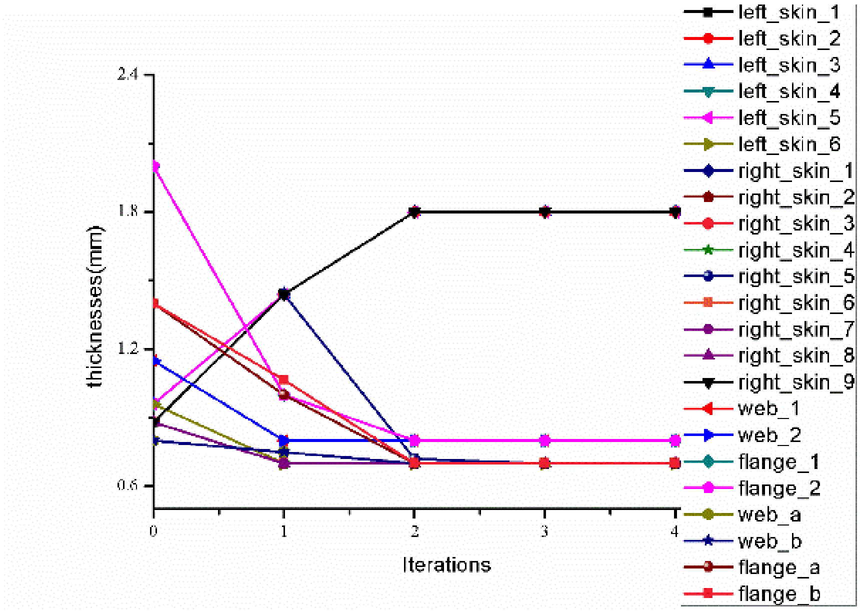

Figure 14 – The variation tendency of design variables.

There are different variation tendencies for skin thicknesses as the maximum thickness of skin equals to 1.8 mm and the minimum thickness of skin equals to 0.7 mm. The region that with thicker skin is mainly distributed on the left side of the optimized tail boom structure, which accords with the principle of load distribution that the left skin should bear large compressive stress. All the thicknesses of frames and sub-frames decreased after optimizing. Similarly, the thicknesses of strengthening frames are larger than that of sub-strengthening frames, which indicates that the strengthening frames are still stronger than sub-strengthening frames after sizing optimization.

## 4.2 Buckling Analysis and Static Strength Analysis of Structure

According to the buckling calculation results, the region that is vulnerable is redistributed and only the upper skin is vulnerable for the first order buckling mode. The outer displacement is limited to the region that between frame 3 and sub-strengthening frame D. And the vulnerable-area of skin decreases compared with that of structure before optimization. Eigenvalue of the first order buckling mode is equal to -1.1161, which indicates that the sub-strengthening frame tail boom meets the requirement of stability design.

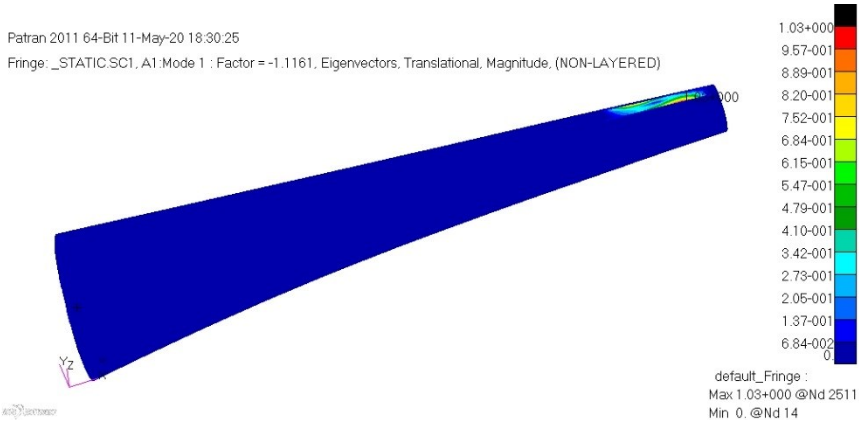

Figure 15 – The first order mode of structure.

Stress contour and displacement contour of optimized tail boom structure are as shown in Figure 16 and Figure 17 respectively.

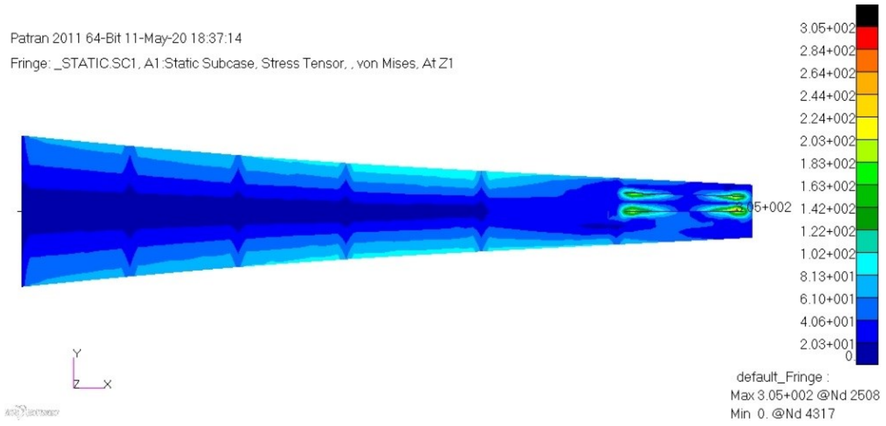

Figure 16 – Stress contour of structure.

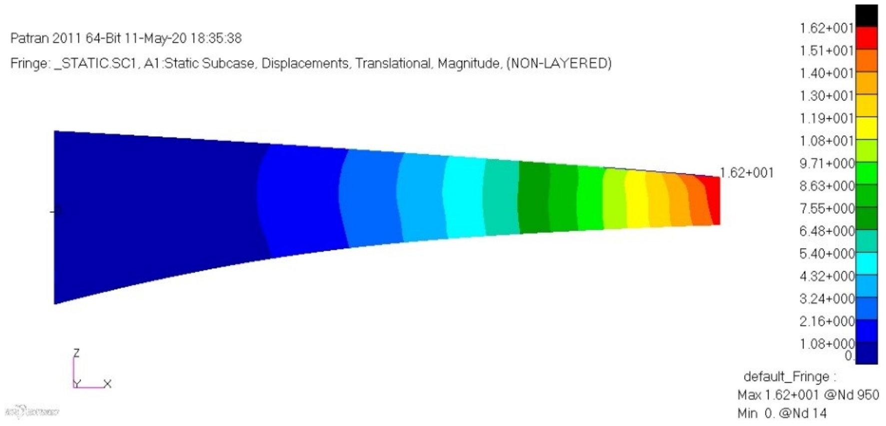

Figure 17 – Displacement contour of structure.

After the optimization, the maximum stress has been increased from 98 MPa to 305 MPa, with an increase of 207 MPa. Stress level of tail boom structure has a great growth compared with that of the preliminary design and the tail boom structure is stressed uniformly, indicating that the material is fully utilized and the structure is efficient. Maximum stress is located in the upper skin that between the frame 3 and sub-strengthening frame D, which is smaller than the failure stress of material. Maximum displacement is located in the end of tail boom with value of 16.2 mm, which meets the requirement of stiffness design.

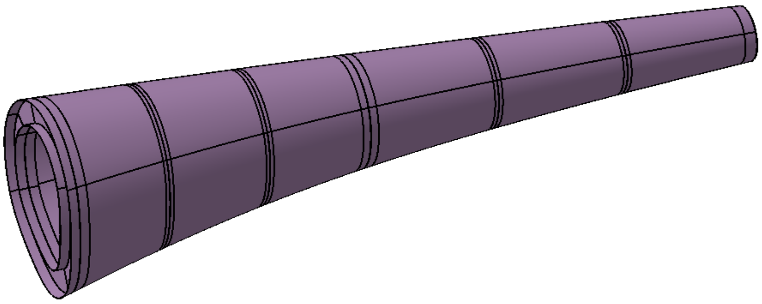

Figure 18 – Sub-strengthening frame tail boom structure.

The optimized sub-strengthening frame tail boom structure is as shown in Figure 18, it is composed of skin, 3 strengthening frames and 4 sub-strengthening frames, and the mass of which is equal to 4.756 kg. The analysis demonstrates that the tail boom meets the requirements of structural design and reduces the structural weight by 7.4%. The structural design of sub-strengthening frame tail boom is reasonable and feasible.

## 5. Conclusion

The structural design of metallic tail boom for an unmanned helicopter that possesses a single rotor and tail-rotor is developed, and the conclusions are as follows:

Optimal load-carrying path of tail boom is acquired on the basis of topology optimization by using HyperWorks and structural layout of tail boom is rapidly determined.

The concept of sub-strengthening frame is proposed, afterwards, the structural design of two kinds of tail booms with conventional monocoque structure and sub-strengthening frame structure are implemented under the constant weight condition. Linear buckling analysis and static strength analysis are carried out under yawing condition. The analysis demonstrates that the introduction of sub-strengthening to the conventional monocoque tail boom structure significantly improves the tail boom's buckling load by 9.2%. Bending rigidity of tail boom structure is improved on account of the introduction of sub-strengthening frame. And it deserves further attention for helicopter design industry which endeavors to develop high performance lightweight tail boom structures with new manufacture technology.

A sizing optimization model of sub-strengthening frame tail boom structure for weight reduction is constructed and the ultimate parameters of it are determined. The results manifest that the optimized tail boom not only meets the requirements of structural design, but also reduces the structural weight by 7.4%. The structural design of sub-strengthening frame tail boom is reasonable and feasible.

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