Optimal Design of a Typical Fuselage Cross Section for a Certain Type of Civil Aircraft

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Abstract. Optimal design of a typical fuselage cross section for civil aircraft is one of the most important aspects of overall aircraft design. In this paper, a typical cross section of a certain type of civil aircraft (referred to as model A) is taken as an example and compared with a similar model B of strength calculation and analysis of deformation, bending moment, stress and other structural bearing efficiency. The principle of the difference is explored and the principle of engineering design of a typical fuselage cross section is summarized. Then the design of the original cross section is optimized by integrating structural load-bearing efficiency, space arrangement and other factors. Strength evaluation is also carried out. Finally, the optimization plan of a typical fuselage cross section of model A is given.

Keywords: fuselage cross section; structural load-bearing; optimal design

1. Introduction
For the civil aircraft, the selection of a typical cabin cross section is extremely important for the performance, economy and comfort of the aircraft. Realizing the optimal design of the typical cross section of the fuselage is an important measure to improve the overall index of the aircraft. Actually, the design of a typical cabin cross section reflects a trade-off between the comfort level of the cabin and the related parameters such as the weight cost and size increase required to meet that comfort level [1]. In general, for aircraft with pressurized cabins, most of the fuselage cross sections are designed to be circular. However, from the perspective of effective space utilization, the circular cross section will waste space with a cross section diameter that is not particularly large[2]. Therefore, in order to meet the requirements of passenger seats and containers layout for aircraft with smaller diameter, multi-circular cross section is often adopted, which is composed of multiple arcs and smooth transition curve coordinated with it. The arc radius and center position can be flexibly changed according to the needs of cabin layout to achieve full utilization of cabin space [3]. The design of model A fuselage cross section was carried out in the form of a multi-circular section. The fuselage section of similar model B is also shown in figure 1. Compared with model B, the lower half of the typical fuselage section of model A has a smaller radius and a smaller transition radius, but a larger transition area.
2. Problem analysis

According to the difference between the above two models in the typical cross-sectional shape of the fuselage, the strength analysis of the structural bearing efficiency such as deformation, bending moment and stress is carried out. The same finite element model is established, and the same pressurized load is applied. The load balances itself inside the fuselage\[4\]. Three-point static constraint is adopted during the calculation, and the element model is modeled by 13 frames of straight sections. The element attributes are assigned according to the real structure or corresponding parameters \[5\], as shown in figure 2.

2.1. Deformation

Take the middle frame of the straight section for deformation analysis. The deformation results in this paper are all displayed at a magnification of 10 times. The frame of the straight section of model A is deformed outward most in the left and right sides of the cargo hold. The middle of the cabin floor beam is downward, and large displacement of the cargo floor occurs upwards together with the bottom wall panel; The straight fuselage frame of model B has the largest outward deformation in the left and right side areas above the cabin floor, and the displacement occurs toward the inside in the left and right side areas of the cargo, while the cabin floor beams remain basically horizontal. Therefore, the deformation state of the cabin floor beam of the straight section of model B is better than that of model A, and it is more in line with the design expectations. The deformation is shown in figure 3.
Figure 3. Deformation of typical fuselage cross section of model A and model B

2.2. Bending moment distribution
The bending moment distribution of the inner end and the distribution of the floor beam of the left frame of the middle straight fuselage frame is compared. The bending moment distribution of the straight fuselage frame of model B is more uniform than that of model A, and the bending moment of the floor beam is much smaller. Therefore, the bending moment distribution of the straight fuselage frame and floor beams of model B is more reasonable than that of model A. The bending moment distribution is shown in figure 4.

Figure 4. Comparison of bending moment distribution of fuselage frame and floor beam of typical cross section between model A and model B

2.3. Stress distribution
The stress analysis on the inner and outer edges of the left side frame of the middle straight fuselage frame is carried out. The stress distribution on the edges of typical straight fuselage cross section of model B is more uniform and reasonable than that of model A, and the load is smaller. The stress distribution is shown in figure 5.
2.4. Influence of structural weight gain

If the cross section of the fuselage remains unchanged, the local structural parameters between the cabin floor and the cargo floor of typical cross section of model A are strengthened in accordance with the design of equal stress level, so that the stress level of the straight section of the fuselage of model B can be reached, and the resulting weight is as high as 108.7 kg. Comparison of stress on the inner and outer edge of typical fuselage cross section frame of model A and model B after partial reinforcement with twice the supercharged load is shown in Figure 6.

2.5. Conclusion

It can be seen from the above that when the same structural parameters are used for design, the typical cross section parameters of the straight fuselage of model B are more reasonable, and the structural bearing efficiency is higher. If the straight fuselage of model A is partially reinforced to achieve a considerable stress level, an additional weight of about 108.7 kg is required. At the same time, the area of the triangular section of the fuselage of model A is smaller than that of model B, which increases the difficulty of system arrangement in the triangle. Therefore, the existing fuselage cross section of model A needs to be optimized.
3. Optimal design

3.1. Principle research
To better illustrate the effect of differences in fuselage cross-sectional shape on frame load-bearing efficiency, three 1/4 arcs of different diameters were tangentially docked to one 1/4 arc, as shown in figure 7. Uniform normal load is applied, and it is found that the distribution of the axial force at the tangent point is not much different, but the bending moment is abrupt, and the greater the radius change, the greater the abrupt gradient.

Figure 7. Schematic diagram of theoretical analysis and comparison of the cross section

It can be inferred that the difference between the radius of the upper and lower semicircle of the straight fuselage cross section of model A is large and the transition area is long, so the frame load between the cabin floor beam and the cargo floor is too large.

3.2. Cross section data analysis of model B
This article makes an in-depth study on the geometric data and design rules of the typical fuselage cross section of model B. It is found that the transition arc of the upper and lower circles of model B is short, and the upper and lower end points of the transitional arcs are equal in distance to the surface of the floor. At the same time, on the premise that the radius and total height of the upper half of the cross section remain unchanged, change the distance between the center of the upper and lower circles, the absolute difference between these two values are showing an increasing trend. It can be inferred from this: a) Model B has undergone detailed optimization design in the design of the transition arc length; b) the midpoint of the transition arc in height is near the upper surface of the floor, and the structural load-bearing efficiency is the highest.

3.3. Cross section data analysis of model A
By comparing the geometric data, it is found that the transition circle of the fuselage cross section of model A is too long, and the absolute difference between the upper and lower end points of the transition arc and the upper surface of the floor is too large. Compared with model B, the lengths distribution of transition arc and lower arc of model A has changed drastically, the cross-sectional area is reduced by 0.016%, and the triangle area is reduced by 4.695%. The reduction of the triangle area leads to the difficulty of system arrangement. The relevant data comparison is shown in table 1.

Table 1. Comparison between typical cross section of model A and typical cross section of model B

| Relative value to model B | Triangle area | Cross section area | Transition arc length | Lower arc length | Cross section circumference |
|--------------------------|--------------|--------------------|-----------------------|----------------|---------------------------|
| Model B                  | 0%           | 0%                 | 0%                    | 0%             | 0%                        |
| Model A                  | -4.695%      | -0.016%            | 53.4%                 | -23.45%        | 0.002%                    |
3.4. Plan optimization
Based on the above analysis, at the same time, in order to minimize the amount of change and the impact of the cross section change, the following optimization principles are determined:

a. The arc radius of the cross section shape should be as close as possible, and the length of the transition arc should be shortened as much as possible, so as to benefit the bearing efficiency of the structure;
b. Keep the radius of the upper circle on the original cross section unchanged;
c. Keep the total height of the original cross section unchanged;
d. Optimize the upper and lower center distances of the design variables (i.e. changing the radius of the lower circle) to make the transition arcs evenly distributed near the floor plane;
e. Strive to make the cross section circumference as small as possible to facilitate drag reduction.

Based on this, this paper developed two new typical fuselage cross sections.

Plan one: reduce the center distances of the upper and lower circle, so that the midpoint of the transition arc in height is near the upper surface of the floor; Plan two: further reduce the center distances of the upper and lower circle, so that the center distances are equivalent to that of model B. The optimization plans are shown in figure 8.

![Figure 8. Improvement plan one and plan two of typical fuselage cross section of model A](image)

The data comparison of improvement plan one, two and model A, model B is shown in table 2.

| Model          | Triangle area | Cross section area | Transition arc length | Lower arc length | Cross section circumference |
|----------------|---------------|--------------------|-----------------------|-----------------|----------------------------|
| Model B        | 0%            | 0%                 | 0%                    | 0%              | 0%                         |
| Model A        | -4.695%       | -0.016%            | 53.4%                 | -23.45%         | 0.002%                     |
| Improvement plan one | 3.176%     | 0.453%             | 0.461%                | 0.267%          | 0.230%                     |
| Improvement plan two | 2.890%     | 0.463%             | -6.705%               | 3.334%          | 0.235%                     |

Using the same finite element analysis method as in Chapter 2 of this article, the structural load analysis of the two improvement plans is carried out. The deformation and bending moment distribution are shown in figure 9-10.
Figure 9. The deformation of fuselage section of model A for improvement plan one and plan two

Figure 10. Comparison of the distribution of bending moments of the straight frame fuselage frame

4. Conclusion
The distribution of bending moment and deformation of the fuselage frame of the plan one and plan two have been greatly improved compared with the original plan. The peak and valley values of the bending moment decreased significantly. The stress distribution of the fuselage frame is more uniform, which improves the structural efficiency and realizes the weight reduction of the structure. The distribution of bending moment and deformation of the fuselage frame of plan one is equivalent to those of model B. Although the cross-sectional area is increased by 0.453% compared to model B, the triangle area is increased by 3.176%, Which is beneficial to solve difficulties in system layout.

It is determined that improvement plan one is adopted as a typical fuselage cross section for the engineering implementation of model A. The comparison between plan one and the original cross-section is shown in figure 11. It can be seen that compared with the original cross-section, the roundness of the cross section of plan one is better, which is conducive to structural bearing.
Figure 11. Comparison of optimization plan one with the original cross section of model A (Black solid line is the improvement plan one, red dotted line is the original cross section)

By optimizing the design of the typical fuselage cross section of model A, the principle of cross section design is explored, the influencing factors and design principles of cross section design is mastered, which accumulated good experience for the subsequent design of aircraft.

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