The Forward Fuselage Rigidity Design Based on Sensitivity Analysis of The Aircraft

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Abstract. In this paper, structural characteristics of the forward fuselage of an aircraft were analyzed. Loadbearing characteristics of longitudinal members and transverse members of the forward fuselage were summarized. After analysis, longitudinal members were identified as main factors that affected structural deformation. Then, finite element analysis and sensitivity analysis methods were combined to determine accurate stiffness sensitivity parameters of the forward fuselage structure. Through analysis of the displacement sensitivity curve, the law of changes in stiffness of the forward fuselage with changes in sizes of longitudinal members was found out. Design requirements on stiffness of the forward fuselage were well satisfied by controlling parameters on purpose. Then, some experiments were designed to compare calculated displacements of the forward fuselage. Experiment results proved the accuracy of the proposed analysis method, allowing designers to get rid of their experience-based the forward fuselage stiffness design. The proposed method could also provide some reference for structural design of new or retrofitted planes.

1. Introduction

Modern fighters are more and more complex to meet various functional requirement. The fuselage of an aircraft is generally designed to install various types of equipment to ensure reasonable space allocation and unaffected equipment performance. For the easy installation and maintenance of airborne equipment, the fuselage tends to have many large openings, with discontinuous crossbars. Therefore, the design of fuselage stiffness is a complicated problem. What factors have an impact on the stiffness of the fuselage? How do they affect the fuselage? In the past, these problems were generally solved through experience, which made the stiffness design unscientific and not rigorous. Besides, they would also lead to a mismatch between the material and the structural stiffness, resulting in excessive strength and structural weight.

Sensitivity analysis has been applied in many fields, such as designing variable selection and structural optimization design[1-11]. Through displacement sensitivity analysis, sensitive factors of the structural stiffness of fuselage can be accurately determined. In this case, the physical parameters of components with great impacts can be adjusted purposively, which makes the structural force more reasonable and finally achieves the match between the bearing capacity and structural stiffness.
Therefore, the purpose of reducing aircraft structure weight, saving materials, and improving aircraft performance can be reached.

2. Introduction to the displacement sensitivity analysis method
The structural equilibrium equation is as follows,

\[
[K][u] = \{P\}
\] (1)

Where \([K]\) refers to the overall stiffness matrix of the structure, \([u]\) represents the nodal displacement, and \(\{P\}\) represents the nodal load. The differential equation of Equation (1) to the design variables is described as:

\[
[K]\frac{\partial\{u\}}{\partial x_i} + \frac{\partial[K]}{\partial x_i}\{u\} = \frac{\partial\{P\}}{\partial x_i}
\] (2)

When \(\{P\}\) is independent of the design variables, it can be obtained according to Equation (2) that

\[
[K]\frac{\partial\{u\}}{\partial x_i} = -\frac{\partial[K]}{\partial x_i}\{u\}
\] (3)

where \(\frac{\partial\{u\}}{\partial x_i}\) is the sensitivity of the structural displacement to the design variables, namely, the displacement sensitivity.

\(\frac{\partial[K]}{\partial x_i}\) can be calculated by calculating each element and then assembling. The element stiffness matrix is presented by isoparametric element as:

\[
[K]^e = \int v [B]^T [D][B][J] d_v
\] (4)

where \([B]\) refers to the strain matrix, which is related to the structural parameter \(x_i\), \([D]\) represents the physical stiffness matrix, \([J]\) represents the jacobian transformation matrix, and \(v\) is the volume.

\[
\frac{\partial[K]^e}{\partial x_i} = \int v \frac{\partial[B]^T}{\partial x_i} [D][B][J] d_v + \int v [B]^T \frac{\partial[D]}{\partial x_i} [J] d_v + \int v [B]^T [D] \frac{\partial[J]}{\partial x_i} d_v
\] (5)

See matrixes \([B]\) and \([J]\) in the references [12-15].

3. Case analysis (taking the fuselage stiffness design of an aircraft as an example)

3.1. Determination of influencing factors
Due to the redesign of structures such as the equipment cabin, the fuselage stiffness of aircraft changes. Through analyzing the structural characteristics of the aircraft, it is found that the longitudinal components of the fuselage mainly include the floor, the longitudinal wall, the side plate, the skin, and the radome, while the transverse members are mainly composed of the fuselage frame. The transverse members, mainly used for maintaining the shape, have little effect on the Y-direction deformation of the aircraft. Therefore, the longitudinal components are the major factors influencing the structural deformation. This analysis aims to achieve the correspondence between the structural deformation and the designed reference values by scientifically changing the geometric parameters of these components. Figure 1 shows the structures of the floor, longitudinal wall, side plate, skin, and radome, and Table 1 indicates the specific dimensional changes.
Table 1. Thickness parameter ranges of the longitudinal components of the fuselage structures.

| Number | Component             | Thickness variation range (mm) |
|--------|-----------------------|-------------------------------|
| 1      | Upper and under floors| 1.5～3                        |
| 2      | Longitudinal wall     | 1.5～3                        |
| 3      | Skin                  | 0.8～1.5                      |
| 4      | Side plates           | 1.5～3                        |
| 5      | Radome                | 3～5                          |

3.2. Displacement sensitivity analysis
The model shown in Figure 2 is modeled using Patran, and the displacement sensitivity analysis is performed on Point 1 and Point 2. Figure 3 shows the displacement change curves of the two points as the thickness parameters of the longitudinal components change. Figure 4 shows the sensitivity change curves of the two points as the thickness parameters of the longitudinal components change.
Figure 2. Fuselage structure and sensitivity analysis positions

Figure 3. Displacement change curves of Point 1 and Point 2 as the thickness parameters of the longitudinal components change

Figure 4. Sensitivity change curves of Point 1 and Point 2 as the thickness parameters of the longitudinal components change

Figure 3 suggests that the thickness variation of the skin has the most significant influence on the displacement of Point 1, followed by the thickness of the radome. According to the result of the
displacement sensitivity analysis at point 1 in Fig. 4, Point 1 is most sensitive to the thickness of the skin. Besides, Point 1 is also sensitive to the thickness of the radome because there is only one longitudinal member, the radome, in front of Frame 1.

It can also be seen from Figure 3 that the thickness variation of the skin has the greatest influence on the displacement of Point 2, while the thickness variation of the other longitudinal members has little effect on it. According to the result of the displacement sensitivity analysis at point 2 in Fig. 4, Point 2 is most sensitive to the thickness of the skin. Since the radome is located in front of Frame 1, its thickness change does not affect Point 2. The displacement sensitivity analysis curve of Point 2 in Fig. 4 also proves that.

Through the above sensitivity analysis curve, it is clear that the skin thickness has the most considerable influence on the structural stiffness of Frame 4 of the fuselage. By purposefully controlling skin thickness and other parameters, the model can be adjusted to achieve the design target of fuselage stiffness. The comparison of the calculated displacement and design values of the fuselage of the aircraft is shown in Table 2 and Figure 5.

Table 2. Comparison of the computational displacement and design values of the fuselage of an aircraft (mm)

| Location | Coordinate | Calculated value | Designed reference value | Calculated value / Designed reference value |
|----------|------------|------------------|--------------------------|-------------------------------------------|
| 1        | 774        | -3.98            | -4.16                    | 0.96                                      |
| 2        | 1549       | -2.68            | -2.73                    | 0.98                                      |
| 3        | 2349       | -1.24            | -1.34                    | 0.93                                      |
| 4        | 2908       | -0.74            | -0.74                    | 1.00                                      |
| 9        | 4420       | 0.00             | 0.00                     | -                                          |

![Figure 5. Comparison of calculated displacement and design values of the fuselage of an aircraft](image)

4. Conclusion
Structural stiffness design is an indispensable part of the aircraft design. Due to the pursuit of combat performance, the weight control on modern aircraft is more and more strict. It is necessary to perform structural sensitivity analysis to get rid of dependence on human experience, scientifically and rationally select the physical parameters of the components, and match the bearing capacity with the structural stiffness, thus achieving structural optimization. In this paper, the finite element analysis technology and the sensitivity analysis method are fully utilized to determine the stiffness sensitivity
parameters of the fuselage structure accurately. Through controlling the parameters purposefully, the design requirements of the fuselage stiffness of the aircraft are well achieved, which provides a reference for the design of the aircraft structure.

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