A Design Method for Twist Distribution along Wing Span

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Abstract. A design method for wing jig shape twist is proposed. Target cruising aerodynamic loads are applied to structure model, and the deformation converge gradually using predictor-correction displacement iterative method. When ensuring the relative twist distribution in the streamwise section, a wing jig shape with straight leading ledge is created, then an aeroelastic coupling iteration is started to achieve the deformed elastic cruising shape. Taking a large aspect ratio swept wing as an example, analysis results show that the deformed elastic cruising wing had an identical streamwise twist distribution compared with rigid designed cruising shape. Sectional lift distribution along with pressure distribution matches well with that of the designed cruising shape, and the drag gap among the is not significant. There might be some change in shock wave chord position between elastic cruising wing and designed cruising wing for outboard wing section. By slight adjusting twist with unchanged airfoil profile, the difference above could be improved.

1. Introduction
Large aspect ratio wings are widely used in modern civil aircraft, which can cruise at high transonic Mach number. Due to the influence of the static aeroelasticity of the structure, the wing deformation includes deflection and torsion along the span, and the geometric twists change accordingly, which will cause the redistribution of aerodynamic load \cite{1,2}. The aerodynamic characteristics of aircraft will change obviously due to the effect of aeroelastic deformation. The conventional design flow of civil aircraft wing is to obtain the optimal aerodynamic shape designed at certain cruising point through aerodynamic optimization \cite{3}. Based on the designed cruise shape, the design of the jig shape used for manufacture can be carried out, so that the aerodynamic performance of the cruise design state can be restored. The static aeroelastic effects on elastic deformation and load redistribution are considered in jig shape design \cite{4}.

In this paper, a predictor-corrector displacement iterative method is proposed. The aerodynamic load of rigid cruising design state is obtained by N-S equations. The load is applied to the structural model and the calculated displacements are reversed to put into the original structure model. After the twist solution is obtained by iterative solution until the displacement converges, the jig shape is created. The twist distribution, load distribution, and pressure distribution are compared between the elastic cruising shape deformed from the jig shape and the rigid designed cruising shape. There may be differences in the position of the shock wave in sections along the wing span near the wingtip, and the twists are slightly changed to improve the difference of the shock wave in the chord without changing the airfoil.
2. Technical methods

2.1 Predictor-Corrector displacement iterative method

The design cruising shape has a straight leading edge, but is twisted in each section to achieve the desired pressure distribution. The jig shape is obtained by changing the twists of the designed cruising wing.

The aerodynamic distribution of the designed cruising shape is taken as the target design load, which would be calculated based on N-S equations. The aerodynamic load is extracted and interpolated to the finite element model using an integral method. The structural deformation is obtained by solving the static equilibrium equation (1).

\[ Kq = F \]  

Where, \( K \) is a structure stiffness matrix; \( q \) denotes finite element node displacement, \( F \) is a load vector. The main procedures are as follows: a) Prediction process: the cruising design load is applied to the finite element model (abbreviated as FEM), thus the wing is accordingly deformed, and then the displacements are reversed to deform the original model so as to produce a new shape; b) Correction process: When applying the target load to the new shape from the previous step, the model is deformed to a new position again, and compared it with the initial FEM model. If the location difference is larger than the tolerance, this iterative process will continue until convergence.

The initial jig shape obtained by the iterative process above is bent down, and the wing would not be designed to be bent because of the requirements from manufacturing and assembly process. The wing leading edge of a jig shape is needed to maintain the same straight line as that of the designed cruising shape. The streamwise twists of the swept wing are affected by both the bending and torsion of the wing. Therefore, it is necessary to measure the geometric twist angle distribution of the initial jig shape and the designed cruising shape in the streamwise direction. The difference between them represents the streamwise twist increment caused by the target aerodynamic load. When the relative twist distributions along wing span are applied to the designed cruising shape, the modified jig shape can be achieved by ensuring the same straight leading edge [5]. Predictor-Corrector design flow for entire jig design is shown in figure 1.
2.2 shock position adjustment method

The objective of this section is to study whether additional design iterations can produce better shock position matching. Firstly, the function between the shock wave position and the wing twist is created. In order to simplify the analysis, the wing twist increment is replaced by the angle of attack increment. The angle of attack sweep for the rigid designed cruising shape is calculated by CFD, and the change of shock position is measured. These examples are used to create the ratio of the chord position of the shock wave to the angle of attack, as shown in the Equation (2).

\[ k = \frac{\Delta x}{C (\Delta \alpha)}^{-1} \]  

Where, \( k \) is a shock wave position ratio, \( \Delta x \) is a shock chord position difference, \( C \) is a local chord length, \( \Delta \alpha \) is an angle of attack increment.

Then, the chord position difference between the elastic cruising wing and the designed cruising wing is measured, and the twist increment is calculated along the wing span. Finally, the twist angle increment is applied to the original jig shape. By CFD/CSD aeroelastic coupling simulation, a new elastic cruising shape is obtained, which is compared with that of the rigid designed cruising shape. The shock position adjustment process is as shown in the figure 2.
3. An example of application
Taking a large aspect ratio swept wing as an example, the jig shape is designed. The finite element model adopts a shell-rod model, and the aerodynamic model is dispersed into structured grids. The cruise Mach number is 0.84 and the lift coefficient is 0.49. The constant lift calculation is used to ensure that the aircraft is in the same flight condition, and the angle of attack of the elastic wing is changed so that the total wing lift can meet the design requirements in static aeroelastic balance.

The aeroelastic effect of the swept wing in flight results in a negative additional twist along wing span, which makes the effective angle of attack decrease and the actual lift become smaller. In order to meet the design requirements of flight characteristics, it is necessary to design a positive pre-twist angle for jig shape, so that the flight quality of an elastic wing is not affected by aeroelastic deformation.

After the wing jig shape is created, the aeroelastic coupling iteration is started until the result converges, and the deformation of the wing reaches a stable state, called as the elastic cruise shape. The comparison of different shape is shown in figure 3, as seen the elastic cruising shape is above the designed cruising shape. The streamwise twist distribution of the elastic cruising wing is compared with that of the designed cruising shape. As shown in figure 4, they have almost the same twist distributions, the difference is less than 0.03degs.

Figure 3. Comparison of the elastic cruising shape and the designed cruising shape.

Figure 4. Comparison on twist under different wing shapes.
The load distribution along the wing span has a significant effect on the vortex-induced drag. Therefore, the elastic cruising shape and the designed cruising shape should have a similar span load. The sectional normal lift of both shapes are extracted along the wing span. As shown in figure 5, overall, the lift span distribution of the elastic cruising shape matches well with that of the designed cruising shape. The drag difference between them is less than 1.5 counts.

![Figure 5. Sectional normal force distribution under different wing shapes.](image)

From figure 6 to figure 7, the pressure distributions are compared. The overall pressure distribution matches closely. There is a slight difference in the position of shock waves in the outboard wing which may be due to the wing deformation resulting in interference between the spanned lift vectors.

![Figure 6. Comparison of the pressure distribution in wing root section.](image)

![Figure 7. Comparison of the pressure distribution in the outboard wing section.](image)

As shown in figure 7, the shock position is adjusted from the initial offset from the original designed wing chord to about 2.5%, reducing to about 1.5%. The twist of the jig shape is adjusted to achieve a slight improvement of the shock position, but the influence of the wing span load is negative, and the twist of the outboard wing is slightly reduced. Figure 8 shows a slight increase in the sectional...
lift of the inboard wing and a significant decrease in the outboard wing. The difference in shock position does not mean that the jig shape is improperly designed.

Figure 8. Cn distribution after adjustment of the shock wave chord position.

4. Conclusion
In this paper, the predictor-corrector displacement iterative method for jig shape design is developed, which can quickly obtain the jig shape that meets the requirements of engineering design. The correctness of the method is verified by an example. The streamwise twist is consistent with the designed cruise shape, and the aerodynamic characteristics of the design cruising shape are effectively restored including the lift distribution and drag characteristics. Based on the results of this paper, the slight adjustment of twist for the jig shape can improve matching of the shock wave position of the outboard wing, but the shock position and the span load can not match at the same time. This may be caused by the 3D effect of the deformable wing.

Reference
[1] Xiong Juntao, Qiao Zhide, Yang Xudong, et al. An aerodynamic shape optimization of transonic wing design method for aeroelastic system[J]. Acat Aerodynamica Sinica, 2009, 27(2): 154-159. (in Chinese)
[2] Chen Guibin, Zou Congqing, Yang Chao. Aeroelastic design basis [ M], Beijing: Beijing University of Aeronautics and Astronautics Press, 2004. (in Chinese)
[3] Xie Meng Cheng Pan Xue Fei. Design and Analysis of Wing Jig-Shape by Different CFD Methods[J]. Civil Aircraft Design and Research, 2011, 4:16-17. (in Chinese)
[4] LiangQiang, Yang Yongnian,YeZhengyin. Analysis of Jig-Shape Design for Elastic Wing[J]. Journal of Northwestern Polytechnical University, 2002, 20(2):262:264 (in Chinese)
[5] Yang Guowei, Zheng Guannan. Aircraft Jig Shape Correction Method Based on Static Aeroelastic Analyses [J]. Advances In Aeronautical Science And Engineering, 2011, 2(2):143-150. (in Chinese)