A Loose Coupling Method on the Twist Angle Optimization of Jig Shape Wing

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Abstract. When we design the 3D wing of an airplane, a cruise-shape wing will be designed first, which has the most ideal aerodynamic pressure distribution. In the real flight the wing will be deformed by the aeroelasticity, which changes the pressure distribution. The twist angle will be optimized to redistribute the pressure on the deformed wing along the spanwise, and thus the pressure distribution can be similar to the ideal cruise shape. A loose coupling method is developed to optimize the twist angle of the jig shape wing, which can be divided into two phase and is able to lower the time and computation resource compared to the tight coupling effectively.

1. Introduction

Aeroelasticity problem is quite complicated to solve in aerospace engineering as CFD (computational fluid dynamics) is coupled with FEM (finite element method) and thus a robust computation cycle need to be designed to transfer the information between the structure and the aerodynamic computation, but coupled numerical method has the potential to be the powerful tool in the jig-shape optimization algorithm [1].

Jig-shape optimization is one popular application of coupled aerodynamic and structural optimization. First, the cruise shape configuration of an aeroplane is designed for the ideal aerodynamic performance. Aerodynamic loads computed using jig shape configuration, however, can cause structural deformation due to the flexibility of the structure. These structural deformations then change the aircraft configuration for the aerodynamic load computation, affecting the structural deformation once again, and finally lowering the aerodynamic performance [2]. The target of the jig shape optimization is to compensate the aeroelastic effect and to approach the designed cruise performance around the cruise condition [3]. The optimization procedure is coupled in a tightly manner, which means the coupled aerodynamic and structural problems are solved simultaneously [4] [5]. For the aerodynamic solver in the coupling procedure, the RANS model is necessary as the Euler solver cannot predict the flow separation, which is time and resource consuming for the convergence of the aerodynamic solution and the coupling method [1]. Timothée Achard, Christophe Blondeau, Roger Ohayon put forward an uncoupled idea for the optimization [6], which reduce the time and the computation resource cost in the optimization.

An alternative approach except the method above is to develop a loose coupling optimization method. The method splits the optimization into two phases, and in the first phases the iteration is based on the FEM solution and in Phase II the iteration is based on the CFD solution. The coupled method connect the two phases. The iteration history and the Cp distribution on the wing prove it is an effective and efficient method.
2. Model Description
For the aeroplane design, we have two different models with a same configuration: cruise-shape model and original jig-shape model. The cruise-shape is the ideal shape when the airplane flies in the cruise condition, the jig-shape is the airplane manufactured from the assembling line. The original jig-shape is same with the cruise-shape, and the twist angle along the spanwise will be adjusted for a better aerodynamic performance to offset the aeroleastic effect.

2.1. Configuration for the cruise-shape and the original jig-shape
An aeroplane configuration has been designed, which is a left-half model and includes body, wing, horizontal tail, vertical tail, pylon and nacelle, and this is the cruise-shape configuration and original jig-shape configuration, which is shown in Figure 1.

![Figure 1. Configuration for the Cruise-Shape and the Original Jig-Shape](image)

2.2. Aerodynamic Model
Discretizing the half space with the half model of the cruise shape/original jig-shape aeroplane, a structured mesh is set up for Navier-Stocks equations with 22 million mesh cell. In the CFD computation, k-omega SST is selected as the turbulence model. The mesh is shown in Figure 2.
2.3. Structure Model

The FEM mesh is set up independently, and the grid point is not one on one corresponded with the aerodynamic surface mesh, so the load transfer between two different meshes is necessary.

The four edges of the wing box are beams which definite the deflection of the wing. The upside front beam is the axis of the twist angle of the wing. In this optimization, only twist angle will finally be updated but not the deflection of upside front beam because the factory will manufacture the same beam as the cruise shape.

The surface mesh of the aerodynamic surface will be partitioned into a lot of subsurface which involves only one FEM surface point. The load on the FEM point will be integrated from the distributed pressure on the aerodynamic subsurface. Considering the thrust of the engine, a point force is added. The FEM model is shown in Figure 3.
3. Methodology: Two Phases of the Inverse Optimization Procedure

The optimization procedure can be divided into two phases and four more configurations are generated except the cruise shape and the original jig shape. The new configurations are the preliminary jig shape, the elastic cruise shape and the optimized elastic shape and the optimized jig shape.

3.1. Phase I: Inverse Loading

The target of Phase I will generate a jig shape which is optimized for the cruise shape. The preliminary jig phase is generated and it is the starting point of the optimization in phase II.

The procedure of Phase I is straight forward and is as follows:

1. Calculate the aerodynamic fluid field of the cruise shape in the cruise condition in a certain Mach number and altitude.
2. Extract the surface pressure on the aeroplane of the cruise shape.
3. Integrate the aerodynamic load of the surface pressure of the jig shape and transfer to the surface node of the FEM mesh.
4. Record the geometry information of the upside front beam from the FEM mesh.
5. Along the spanwise of the wing, cut the wing with some planes vertical to the front beam and obtain the airfoil slices of the wing in different spanwise stands.
6. Calculate the twist angles of the different slices.
7. Iterative process on generating the preliminary jig shape:
   a) Add the aerodynamic load on the FEM nodes.
   b) Calculate the displacement of the FEM nodes compared with the initial coordinates of the node.
   c) Reverse the vector of the displacement.
   d) Add the reversed displacement on the coordinates of all the FEM nodes and update the coordinates of the node.
   e) Go to the step a) or stop the loop if the change of displacement is small enough.
8. Calculate the displacement on each FEM node between the final status and the initial coordinates.
9. Update the upside front beam information temporarily.
10. Cut the wing with the same ratio stand along the wing, vertical to the temporary upside front beam of the deformed cruise shape and calculate the twist angles in the new slices.
11. Calculate the difference of the twist angle in the corresponding spanwise stands and add the difference to the cruise shape configuration.

After the iteration process, the new configuration is the preliminary jig shape. Notice the deflection of the preliminary jig shape is same with the cruise jig shape because in Phase I only the twist angle but not the deflection of the wing is updated.

3.2. Phase II: Direct Optimization of Twist Angle

This phase starts from the preliminary jig shape and, finally achieves the optimized jig shape. The optimization process is time and resource consuming in this phase because of the convergence of the CFD computation. The target of the optimization is minimizing the sum of the variance of the Cp distribution between the cruise shape and the shape we are optimizing. The variables are the twist angle on the different stands of the wing. The only limit of the variables is the twist angles are monotone decreasing from the root to the tip of the wing.

The following steps are operated in Phase II:

1. Cut the cruise shape wing with planes vertical to the upside front beam and obtain the airfoil slices of the wing in different spanwise stands, and record the Cp distribution on each airfoil.
2. Generate the CFD mesh of the preliminary jig shape configuration.
3. Start a fluid/structure coupling computation of the preliminary jig shape and obtain the elastic cruise shape. The elastic cruise shape is the deformed preliminary jig shape as the result of the aerodynamic load, which is the shape in the flight.
4. Update the upside front beam information of the elastic cruise shape.
5. Cut the elastic cruise shape wing with planes vertical to the upside front beam and obtain the airfoil slices of the wing in different spanwise stands, and record the Cp distribution on each airfoil.

6. Iterative process on optimizing the elastic cruise shape
   a) calculate the variance of the Cp distribution of these two shapes.
   b) Adjust the twist angle of the elastic cruise shape to minimize the variance.
   c) Use moving-mesh method to generate new CFD mesh
   d) Calculate the CFD result of the temporarily elastic cruise shape.
   e) Obtain Cp distribution on each airfoil.
   f) Go to step a) or stop the loop if the variance can be lowered any more.

7. Calculate the twist angle difference between final elastic cruise shape and the initial elastic cruise shape and add it to the preliminary jig shape.
   The new shape is the optimized jig shape.

4. Implementation
In the case following, we apply the model in the methodology above. In the cruise condition of flight, Mach number equals to 0.85 and the altitude equals to 35000ft. The Cp of the aeroplane is fixed at 0.48 in the entire optimization procedure, and the fluid solver will look for the angle of attack of the aeroplane in the aerodynamic computation. Gradient Decent is selected in the optimization procedure.

4.1. Phase I
In the Figure 4, the plot shows the difference of the twist angle between the cruise shape (red) and the preliminary jig shape (green).

![Figure 4. The Cruise Shape and the Preliminary Jig Shape](image-url)
4.2. Phase II
Phase II starts from the preliminary jig shape with the fluid structure coupled computation in the cruise condition. We select 27 different slices to calculate the variance of the Cp distribution between the cruise shape and the optimizing elastic cruise shape. To reduce the number of the variables, we define two more limits: the twist angle of the inner wing will not change, which is also corresponding to the physics of the aeroelasticity of the aeroplane; we do not change the twist angle directly, but we select three stands on the wing and set their increments, use the nurbs spline to interpolate all the increment to all the twist angle of the outer wing to generate a new twist angle distribution. To balance the efficiency in this problem, we chose three twist angle stands to optimize the entire Cp distribution along the wing span, so the Cp of the outer wing of the elastic cruise shape will not be totally same with the cruise shape.

Figure 5 shows that shape (green) comparison to the preliminary jig shape (blue).

Figure 6 is the variance history in optimization iteration of the twist angle.
Some typical slices are chosen and number series of the stand position increases from the root to the tip of the wing. The blue line “std_cp” is the Cp of the cruise shape, the red line “test_cp” is the Cp of the optimized elastic cruise shape and the green line “start_cp” is the Cp of the elastic cruise shape. From the comparison, it is obviously that the optimization is effective, which is shown in Figure 7.

Figure 8 shows the change of the twist angle in the optimization.
5. Conclusion

To recover the performance of the wing from the jig shape which is manufactured in the factory and is also deformed because of the aerodynamic load in the flight, to the cruise shape which is the ideal shape when the aeroplane is designed, the optimization on the twist angle of the wing is applied with two phases: the displacement iteration and the optimization algorithm. In this paper, we design an aeroplane CFD model and FEM model, develop a loose coupling method and test the methodology in the cruise condition, which is effective and valuable in industry.

In most of the case, the aeroplane flies in the cruise condition, but for the robust design, in the future research, other flight condition will be considered for this optimization, for example, non-cruise condition as Mach number equals 0.7 and the altitude equals 15000 feet, which is robust in multi flight condition, or on the boundary of the flight envelop as Mach number equals 0.95 and the altitude equals 30000 feet, which is the designed for the safety. For these cases, multi objective optimization method is necessary as NSGAII and we need evaluate the weight of different flight condition in the optimization. Thus the method developed above is a good step stone for the future research in the aeroelasticity design of the aeroplane.

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