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Efficient aero-structural design optimization: Coupling based on reverse iteration of structural model

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Traditional coupled multi-disciplinary design optimization based on computational fluid dynamics/computational structure dynamics (CFD/CSD) aims to optimize the jig shape of aircraft, and general multi-disciplinary design optimization methodology is adopted. No special consideration is given to the aircraft itself during the optimization. The main drawback of these methodologies is the huge expanse and the low efficiency. To solve this problem, we put forward to optimize the cruise shape directly based on the fact that the cruise shape can be transformed into jig shape, and a methodology named reverse iteration of structural model (RISM) is proposed to get the aero-structural performance of cruise shape. The main advantage of RISM is that the efficiency can be improved by at least four times compared with loosely-coupled aeroelastic analysis and it maintains almost the same fidelity of loosely-coupled aeroelastic analysis. An optimization framework based on RISM is proposed. The aerodynamic and structural performances can be optimized simultaneously in this framework, so it may lead to the true optimal solution. The aerodynamic performance was predicted by N-S solver in this paper. Test shows that RISM predicts the aerodynamic and structural performances very well. A wing-body configuration was optimized by the proposed optimization framework. The drag and weight of the aircraft are decreased after optimization, which shows the effectiveness of the proposed framework.

aero-structural optimization, reverse iteration, cruise shape, CFD/CSD, true optimum, semi-coupled

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1 Introduction

The coupling of aerodynamics and structures are very severe for large aspect ratio aircrafts such as large military transport, civil transport and high altitude long endurance UAV. The aerodynamic loads affect the structural deformations, which in turn change the aerodynamic shape. So integrated aerodynamic/structural design optimization is necessary to get the optimum wing. The integrated aerodynamic/structural design optimization has been widely investigated during the last 30 years. Most design optimization methods were based on low-fidelity models such as beam models combined with panel methods in the past. Now in view of the importance of high-fidelity analysis methods to the design optimization, high-fidelity models such as N-S equations, finite element method and so forth are preferred today in integrated aerodynamic/structural design optimization. However, all these high-fidelity models exacerbate the computational burden. Therefore, one of the main tasks of aero-structural design optimization today is to reduce the computational cost and speed up the optimization proce-

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dure.

During the past decade, aero-structural design optimization has developed significantly. Large amounts of researches have been conducted to improve the optimization efficiency. Efficient algorithms were developed by researchers such as tightly coupled CFD/CSD method to enhance the efficiency of static aeroelastic analysis [1]. Some researchers developed effective optimization frameworks for aerodynamic/structural design optimization. These frameworks include optimizations based on genetic algorithm and all kinds of surrogate models proposed by Kumano et al. [2], Zill et al. [3], Rajagopal and Ganguli [4], Nikbay et al. [5], Lian and Liou [6]. After years of rapid development, the surrogate-based optimization entered a bottleneck period, and no breakthrough has been made during recent years. Many researchers construct complex multi-fidelity optimization framework to satisfy the various requirement of different phases of aircraft design [7–12]. Many optimization cases have been done about aircraft design engineering. Some others developed gradient-based optimization to increase the optimization efficiency, and typical work includes those of Martins and Kennedy et al. [13,14], Barceblos and Maute [15], Fazzolari et al. [16], Ghazlane et al. [17].

In all these researches the jig shape was parameterized and optimized, and these optimization methodologies did not represent the characteristic of the aircraft perfectly. Static aeroelastic analyses have to be carried out in traditional aero-structural optimization to obtain both the cruise shape and its aero-structural performance as the aerodynamic and structural disciplines are coupled. This procedure is very time-consuming if high fidelity models such as Euler/N-S equations are adopted. The CFD/CSD analysis have to be performed iteratively during static aeroelastic analysis to get the aerodynamic performance such as lift, drag and structural performance such as maximum stress and displacement of the aircraft. To avoid the repeated aerodynamic/structural analyses, Aly proposed a decoupled approach of aero-structural design optimization [18]. However, the aerodynamic and structural optimizations are conducted sequentially in Aly's work, which could not lead to the true optimal solution of aero-structural design optimization.

One of the characteristics of the aircraft is that the cruise shape may be transformed into the jig shape by a jig shape correction [17]. Jig shape correction gives the jig shape of the aircraft as well as the aerodynamic and structural performance of the aircraft. The aerodynamic design variables affect the structural performance of cruise shape if we parameterize and optimize the cruise shape directly, and structural design variables such as the thickness of skin, the area of beam cap and so forth do not affect the aerodynamic performance of cruise shape. Therefore, the system is semi-coupled from the perspective of the cruise shape. Efficient methodologies can be constructed to get the aero-structural performance of the aircraft according to the convertibility between the jig shape and the cruise shape if we optimize the cruise shape directly, which is one of the main purpose of this paper. Also very efficient optimization framework can be constructed if we optimize the cruise shape directly.

The remainder of this paper is organized as follows: Section 2 describes the two high fidelity models adopted for the multi-disciplinary optimization problem in this paper. Section 3 presents a novel integrated aero-structural optimization framework. Section 4 validates the effectiveness of the proposed aero-structural performance prediction methodology and the optimization framework. The conclusions are drawn in section 5.

2 Aerodynamic and structural analysis method

The flow governing equations are the compressible Navier-Stokes equations

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_{\Omega}\boldsymbol{Q}\mathrm{d}V+\int_{\partial\Omega}\boldsymbol{F}\cdot\hat{n}\mathrm{d}S=\int_{\partial\Omega}\boldsymbol{G}\cdot\hat{n}\mathrm{d}S, \tag{1}$$

where Ω is an arbitrary control volume, $\partial\Omega$ is the boundary of the control volume, and $\hat{n}$ is the unit normal vector at the boundary. $\boldsymbol{Q}$ is the set of conservative flow variables. $\boldsymbol{F}$ is the inviscid flux tensor, and $\boldsymbol{G}$ is the flux tensor associated with viscosity and heat conduction.

These equations are discretized with the cell-centered finite volume method, and Roe scheme is adopted for the space discretization. Turbulent flows are simulated by SA turbulence model. For the time integration, LU-SGS implicit method is adopted [19].

Structural analysis is carried out by finite element analysis.

The aero-structural analysis is performed by using a multi-disciplinary analysis. Disciplines are linked through the exchange of coupling variables, which consist of the vector of external forces returned from the aerodynamic analysis, and the vector of displacements determined by the structural analysis. Because the CFD and CSD models used in the simulation are generated independently, a data transfer between these two kinds of solvers is necessary. Many algorithms have been developed to transfer data between CFD and CSD models, which include IPS (infinite-plate spline), BEM (boundary element method), CVT (constant-volume tetrahedron), radial basis functions (RBF), etc. [19–24]. The RBF method is used in this paper to convert the pressure and displacements in the interface.

3 The aero-structural optimization framework

3.1 The Aero-structural analysis

In common multi-disciplinary design optimization, the jig shape is parameterized and a static aeroelastic analysis is needed to get the aerodynamic and structural performance of the aircraft. A typical static aeroelastic simulation method is the loosely coupled aeroelastic simulation. The procedure to get the structural and aerodynamic performance is described in Figure 1. The CFD solver is used to feature the aerodynamic characteristics, and the aerodynamic load is transferred onto the structural nodes by interface interpolation of fluid-structure interaction (FSI). Then a finite element analysis is carried out to get the deformed aircraft. The CFD grid of this deformed aircraft is regenerated and aerodynamic analysis is conducted again. This procedure will be repeated until the deformation converges. Usually 5–10 iterations are expected for this procedure, which is very time-consuming and inefficient. The mass, aerodynamic forces, maximum displacement and maximum stress of the cruise shape are obtained at last. The aerodynamic design variables affect the structural performance of cruise shape from the perspective of jig shape, and the structural design variables that have no impact on the configuration affect the aerodynamic performance of cruise shape too. Therefore, the system is coupled and inefficient.

To improve the efficiency, we aim to parameterize and optimize the cruise shape directly based on the fact that jig shape correction gives the aero-structural characteristic of the aircraft. The aerodynamic performance of cruise shape can be obtained easily. To get the structural performance of the aircraft, the jig shape corresponding to the cruise shape is calculated firstly. Then the aerodynamic load, the force of gravity of cruise shape, etc., are cast on the jig shape. Finally the structural performance of the cruise shape is obtained by structural analysis.

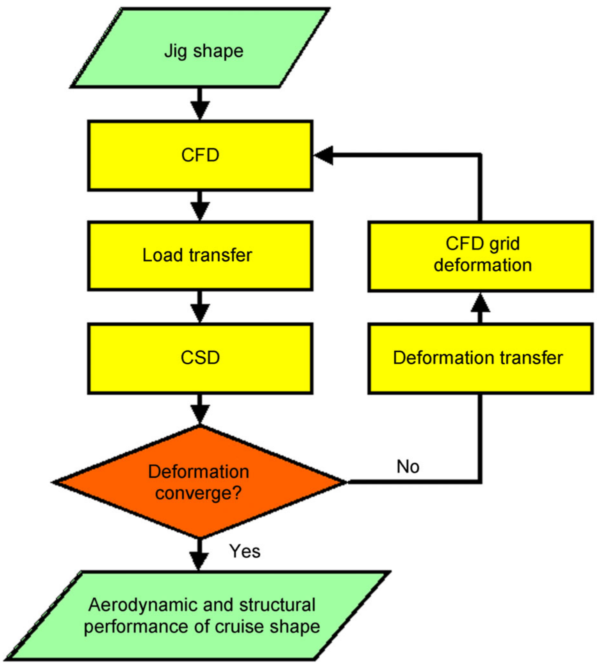

Figure 1 (Color online) Flowchart of typical static aeroelastic analysis.

We adopted Aly's methodology [17] to get the jig shape because it has been widely used in aircraft design. All the forces including the aerodynamic load, force of gravity and so forth are acted in reverse direction on the cruise shape, and the deformed aircraft is the jig shape we wanted. So the displacement of structural nodes can be achieved by solving the following equation:

$$\{X\} = [K]^{-1}\{F\},$$

where $[K]$ represents the stiffness matrix of the cruise shape, $\{X\}$ means the unknown vector of the structural deformation, and $\{F\}$ means the forces including the aerodynamic force, force of gravity, etc., acting on the structure. Adding the coordinates of structural nodes to the corresponding displacements produces the expected jig shape.

Aly's methodology was found not very precise. If we apply the aerodynamic load of cruise shape, etc., to the jig shape, we get the deflected jig shape. It is supposed to be the same as the cruise shape, but actually, it has some difference with the cruise shape. This is mainly because of the difference of the stiffness matrices of these two configurations. We also get the inaccurate structural performance of this aircraft in this way. It will be discussed further in the next section. That's why improvements were made to get jig shape in the past few years [25]. The general improved jig shape correction can be described as follows.

(1) Call the CFD solver to feature the aerodynamic characteristics of the cruise shape and we get the aerodynamic load of the aircraft.

(2) Get the jig shape through Aly's methodology.

(3) Aeroelastic analysis of the jig shape is conducted to get the deflected jig shape.

(4) Compare the displacement of every structural node of the cruise shape and the deflected jig shape. The coordinate difference vector of the corresponding structural nodes is termed as ΔX. If ΔX is small enough, the procedure finishes.

(5) Add $\gamma\Delta X$ to the structural nodes of jig shape and we get the updated jig shape, where γ is a factor between 0 and 1. Go to (3).

As can be seen from this procedure, we get the structural performance of the aircraft according to the displacement of the jig shape at last. The computational expense of this procedure is even large than that of the aeroelastic analysis to get the aero-structural performance of the cruise shape. Therefore, it is not suitable for use in optimization. It is notable that the jig shape deformed into the cruise shape under the forces including the aerodynamic load of the cruise shape at last. This prompts a way of using the loads of the cruise shape to get the deflected jig shape directly without iteratively calling the CFD solver. A novel aero-structural performance prediction methodology named RISM is proposed and shown in Figure 2. It can be described as follows.

(1) Call the CFD solver to obtain the aerodynamic characteristics of cruise shape and we get the aerodynamic load

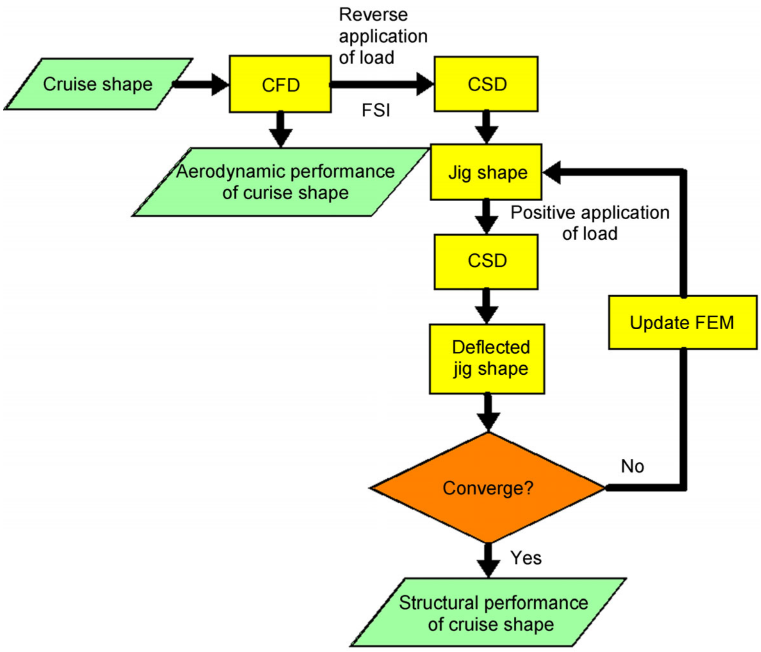

Figure 2 (Color online) Aero-structural analysis.

of the aircraft.

(2) Get the jig shape through Aly's methodology.

(3) Apply all the aerodynamic forces of the cruise shape, the force of gravity, etc., in the right direction to the jig shape to get the deflected jig shape.

(4) Compare the displacement of every structural node of the cruise shape and the deflected jig shape. The coordinate difference vector of the corresponding structural nodes is termed as ΔX, where ΔX is a vector. Add $\gamma\Delta X$ to the structural nodes of jig shape and we get the updated jig shape, where γ is a factor which is larger than 0 and less than 1.

(5) Go to step (3) unless ΔX is small enough

At least 15 iterations are needed in this procedure throughout which the aerodynamic load is invariable.

The vector of converged steady field variables $\boldsymbol{Q}$ has been obtained in the first step of RISM. Based on $\boldsymbol{Q}$ the structural displacement of cruise shape in the second step of RISM is obtained by solving the following equation

$$K_{\text{cruise}}\Delta U_1 - \boldsymbol{F} = 0, \tag{2}$$

where K_{cruise} is the structural stiffness matrix of cruise shape, ΔU_1 is the structural displacement and $\boldsymbol{F}$ is nodal force vector of the aerodynamic forces of the cruise shape, the gravity and so forth in reverse direction.

The above equations can be expressed in the following form

$$S(Q, X_{s1}, \Delta U_1) = 0, \tag{3}$$

where X_{s1} is coordinate vector of the finite element mesh (FEM) of the cruise shape. We get the jig shape in the second step of RISM with the following equations:

$$X_{s2} = X_{s1} + \Delta U_1. \tag{4}$$

In the third step of RISM, the deflected jig shape is obtained by solving the following equations.

$$\begin{aligned} &K_{\text{jig}}\Delta U_2 - F = 0, \\ &X_{s3} = X_{s2} + \Delta U_2, \end{aligned} \tag{5}$$

where K_{jig} is the structural stiffness matrix of jig shape X_{s2} is used to construct the structural stiffness matrix of jig shape, Q, etc., are used to construct the nodal force vector. X_{s3} is the coordinate vector of FEM of the deflected jig shape.

The update of the jig shape in the fourth step of RISM can be represented as:

$$\begin{aligned} \Delta X &= (X_{s3} - X_{s1})\gamma, \\ X'_{s2} &= X_{s2} - \Delta X \\ &= X_{s2} - (X_{s2} + \Delta U_2 - X_{s1})\gamma \\ &= (1-\gamma)X_{s2} + \gamma X_{s1} - \gamma\Delta U_2, \\ X_{s2} &= X'_{s2}. \end{aligned} \tag{6}$$

The essence of RISM is solving the following nonlinear equation:

$$\boldsymbol{K}(X_{s1}, \Delta U)\Delta U + F = 0, \tag{7}$$

where $\boldsymbol{K}$ is the structural stiffness matrix of jig shape, and it depends on the FEM of the cruise shape X_{s1} and the displacement ΔU between the jig shape and the cruise shape.

The procedure of RISM is very similar to that of the jig shape correction method described in ref. [25]. Their main difference exists in that the aerodynamic load imposed on the jig shape. The aerodynamic force of the jig shape in RISM is invariable, whereas it is achieved by aeroelastic analysis in ref. [25]. Obviously, RISM converges at a much reduced computational expense.

There lies an interesting comparison between the procedure of the static aeroelastic analysis and that of RISM. The FEM is unchangeable and the CFD grid and aerodynamic loads update every iteration in the static aeroelastic analysis, whereas the CFD grid and aerodynamic loads are unchangeable and the FEM updates every iteration in RISM.

As can be seen in the procedure of RISM, the CFD solver is called only once to get the aerodynamic performance of cruise shape, and CSD solver is called iteratively. We get the aerodynamic and structural performance of the cruise shape by RISM just like what the aeroelastic analysis can do. Usually we call the CFD solver at least five times in general loosely-coupled static aeroelastic analysis. The expense of structural analysis can be neglected compared with that of aerodynamic analysis. Therefore, the efficiency of RISM can be improved by at least four times compared with the loosely coupled aeroelastic analysis.

3.2 The MDO framework based on RISM

The widely used optimization framework based on the surrogate model and the genetic algorithm is adopted. RISM is used to get the aero-structural performance of the aircraft. The aerodynamic and structural performances are optimized simultaneously. The steps of the proposed algorithm are explained as follows.

Latin hypercube is selected as the sampling method to ensure that all portions of the vector space are represented. The performance of aerodynamics and structure is calculated by the above aero-structural analysis. The Kriging model is adopted to get the objective function based on these samples. The genetic algorithm is used to optimize the Kriging models to get the optimum. The optimum has to be validated by the above aero-structural analysis and added to the sample dataset. When the surrogate approximation model has been updated, the genetic algorithm runs again to get a new optimum. This process continues until the variation of objective function is small enough. The flowchart of the design process is shown in Figure 3.

4 Examples

To demonstrate the effectiveness of the optimization system, a wing-body configuration is optimized. The freestream Mach number is 0.785, and Reynolds number is set to be 2.49×10^7. The grid is generated with a size of 1.8 million. Figure 4(a) displays part of the CFD grid of the aircraft. The deformation of the body is not large and it is supposed to have little influence to the aerodynamic characteristics of the wing-body configuration, so the finite element analysis is performed only on the wing. This technique is also adopted by many researchers frequently [17].

The main load-carrying components of the wing box are considered, including skins, ribs, wing spars, stringers. The front and rear spar are defined at 15% and 65% along the

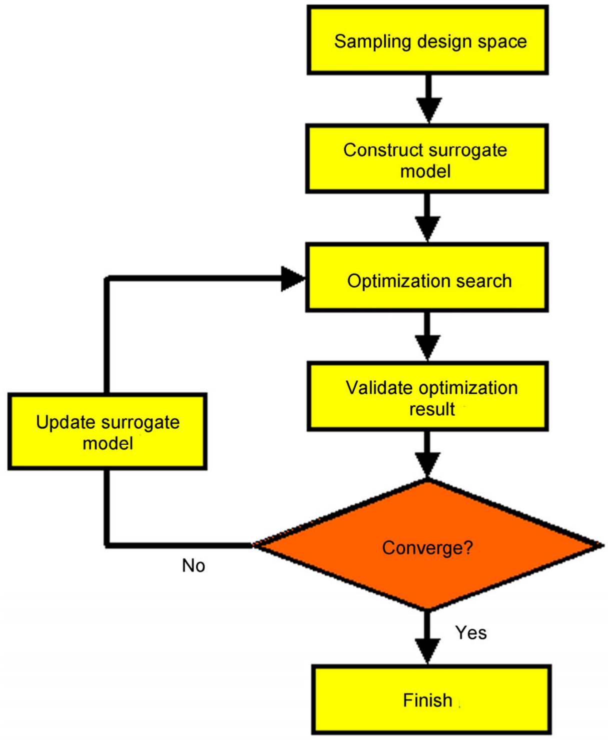

Figure 3 (Color online) Surrogate model-based optimization process.

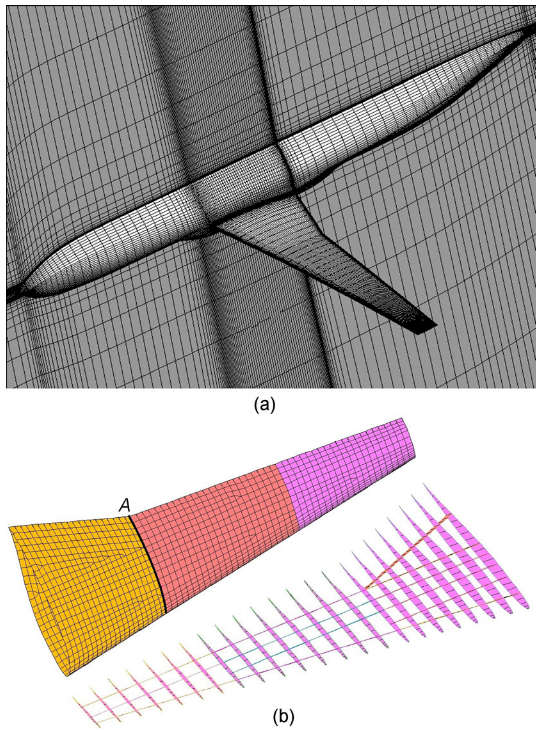

Figure 4 (Color online) CFD grid of wing-body configuration and wing structural model. (a) CFD grid of wing-body configuration; (b) wing structural model.

chord, respectively. The spars and ribs are assumed to be ‘T-beams’. The structural model of skins, ribs and spars are shown as Figure 4(b). The aluminum alloy adopted has the elasticity modulus of 70 GPa and the Poisson’s ratio of 0.33. The ultimate strength of this material is 412 MPa and its density is 2.7×10^3 kg/m^3.

4.1 Validation of RISM

RISM methodology is validated firstly. γ is set to be 0.5. The iteration finished after 15 iterations, and we get the jig shape and the deflected jig shape name DJS1 at last. The semispan of the aircraft is 17.02 m. The maximum displacement of deflected jig shape compared with jig shape is 0.940 m. The comparison of jig shape and cruise shape is shown in Figure 5. The maximum distance between the corresponding nodes of cruise shape and DJS1 is 0.001 m. This means that these two FEM almost coincide. Figure 6 shows convergence history of RISM with different value of γ, where the longitudinal axis represents the maximum distance between the corresponding structural nodes of deflected jig shape and the cruise shape. The structural characteristics predicted by RISM and that of Aly’s method are shown in Table 1. As can be seen, the difference of the maximum displacement predicted Aly’s method and that of static aeroelastic analysis comes up to 0.063 m. The difference of von Mises stress is even larger.

To validate the proposed method further, loosely coupled static aeroelastic analysis of the jig shape achieved by the RISM is carried out. We get another deflected jig shape named DJS2 by aeroelastic analysis. Figure 7 shows the pressure contour of the cruise shape and DJS2 as well as the sectional pressure distribution. As can be seen, the difference is very small except the sectional pressure distribution at wing tip section. The maximum displacement between DJS2 and the jig shape is 0.948 m. The difference of maximum displacement between the DJS2 and the cruise shape is 0.008m, which is negligible. The maximum stress predicted by RISM and aeroelastic are almost the same. Table 2 shows the aerodynamic characteristics of the cruise shape and DJS2. The lift coefficient C_L and drag coefficient C_D of the cruise shape and DJS2 are very close. The difference of pitching moment coefficient C_m of these two configurations is larger than that of the drag coefficient, and this is because of the difference of the wing tip shock location of these configurations. The difference of the cruise shape and DJS2 was caused mainly by the inaccuracy of interface interpolation of FSI.

All these results indicate that RISM predicts the aerodynamic and structural characteristics very well. All theses results build a solid foundation for the following aero-

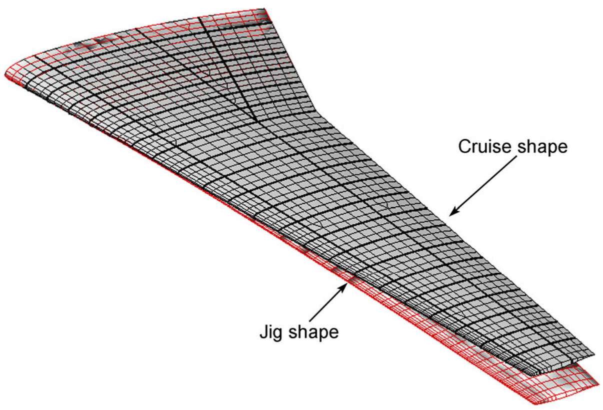

Figure 5 (Color online) Comparison of jig shape and cruise shape.

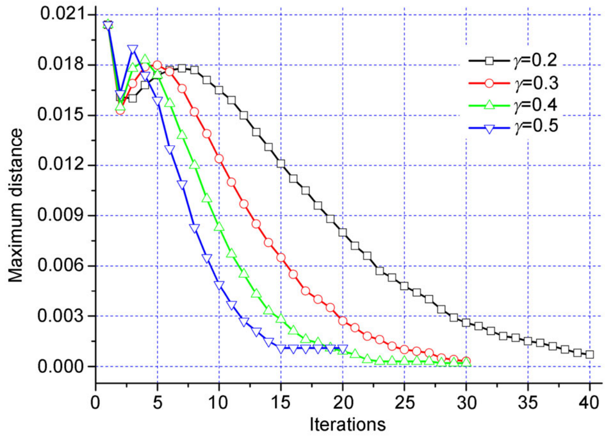

Figure 6 (Color online) Convergence history of RISM.

Table 1 Structural characteristic of the aircraft predicted by various methods

Prediction method	Maximum displacement (m)	Maximum stress (Pa)
Aly’s method	0.877	1.820×10^8
RISM	0.940	2.237×10^8
Static aeroelastic analysis	0.948	2.249×10^8

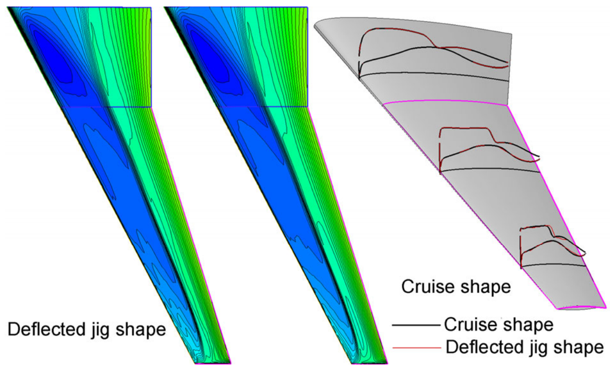

Figure 7 (Color online) Pressure contour of the cruise shape and the deflected jig shape.

Table 2 Aerodynamic characteristics of the cruise shape and DJS2

Configuration	C_L	C_D	C_m
Cruise shape	0.550	0.030228	–0.1131
DJS2	0.550	0.030261	–0.1113

structural design optimization.

4.2 Aero-structural optimization

The planform of wing is parameterized by three variables: semispan, sweep angle and tip chord length. The spanwise location of section A as shown in Figure 4(b) is fixed throughout the optimization. In this work the topology of the structure remains unchanged, which means that the number of spars, ribs and their planform-view locations are all fixed. The FEM is divided into three segments along the span-wise direction. The thickness of skins, area of stringers and area of spar cap of each segment are selected as design variables. Therefore, the number of structural variables is nine, and the total number of design variables is twelve.

The objective is to minimize the drag and weight of the aircraft. During the optimization, the reference area used to calculate the lift coefficient, etc., is fixed to be 126 m^2 for convenience. Three constraints are enforced. One is that the lift must be constant, which means C_L is fixed. The second is that the wing area must be in appropriate range. The last is that the constraint on the maximum stress of material. In our optimization we constrain C_L by periodically adjusting the angle of attack. Now we can summarize the aircraft design optimization problem as follows:

$$\text{Min} \quad C_1D+C_2W$$

$$\text{s.t} \quad \begin{aligned} &C_L = 0.55, \\ &125\ \text{m}^2 < S_{\text{wing}} < 127\ \text{m}^2, \\ &\delta_{\max} < 2.3\times10^8\ \text{Pa}, \end{aligned}$$

where C_1 and C_2 are weight coefficients ($0<C_1$, $C_2<1$, and $C_1+C_2=1$). C_1 and C_2 represent the importance of the aerodynamic and structural disciplines and it depends on the designer. If C_1 is set to be 1, the optimization is a pure aerodynamic optimization. If C_2 is set to be 1, the optimization is a pure structural optimization. C_1 is set to be 0.3 and C_2 to be 0.7 in this case. W is the structural mass of the wing, and D is the drag. $\delta_{\max}$ represents the maximum von Mises stress of the wing. S_{wing} means the area of the wing. The aircraft is optimized by the former optimization framework, and the number of initial samples is 150.

The pressure contour of the aircraft and the planform before and after optimization are shown in Figure 8. The von Mises stress comparison before and after optimization is shown in Figure 9. The aerodynamic and structural characteristics before and after optimization are shown in Table 3. The convergence history is shown in Figure 10. As can be seen, a decrease of 2.5 aerodynamic counts of drag coefficient obtained after optimization with the mass of wing decreased by 4.03%. The shock wave is the main component of drag and the shock wave strength depends mainly on the wing section. Therefore, the improvement of aerodynamic performance is limited.

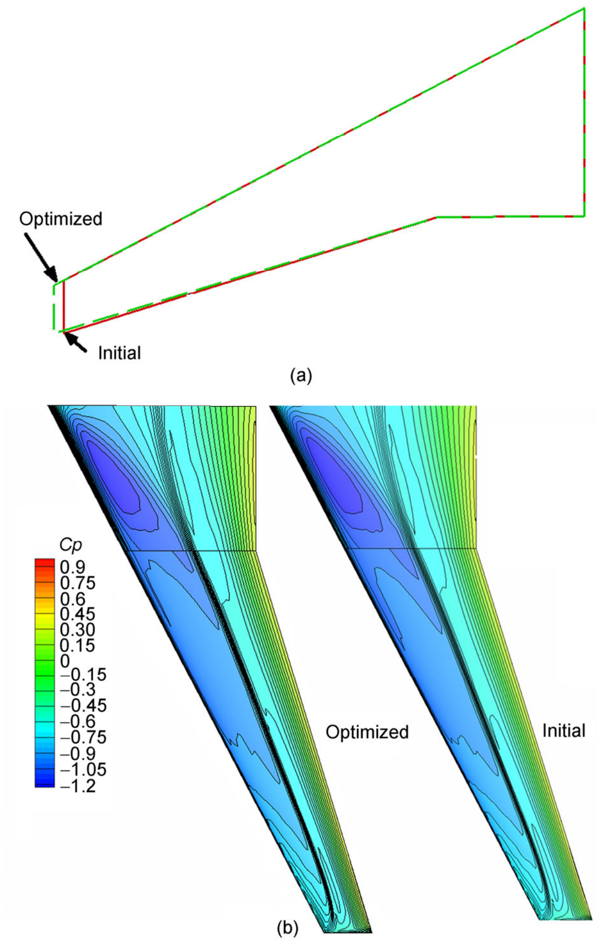

Figure 8 (Color online) Pressure contour and planform comparison before and after optimization. (a) Planform comparison before and after optimization; (b) pressure contour comparison before and after optimization.

Aeroelastic analysis is conducted to the jig shape corresponding to the optimized configuration, and a deflected jig shape named DJS3 is achieved. The aero-structural performance comparison of the optimized configuration and DJS3 are listed in Table 3. As can be seen from Table 3 that performance of DJS3 and the optimized configuration are very close, which verified the correctness of RISM again.

The optimization efficiency can be improved by four times compared with the traditional multidiscipline optimization based on static aeroelastic analysis. The optimization calls 186 times of the CFD solver. This expense is much lower compared with that of the optimization based on genetic algorithm.

5 Conclusions

(1) The test shows that RISM provides very close results to those predicted by a coupled static aeroelastic analysis method with high efficiency. So it is suitable for aero-structural optimizations.

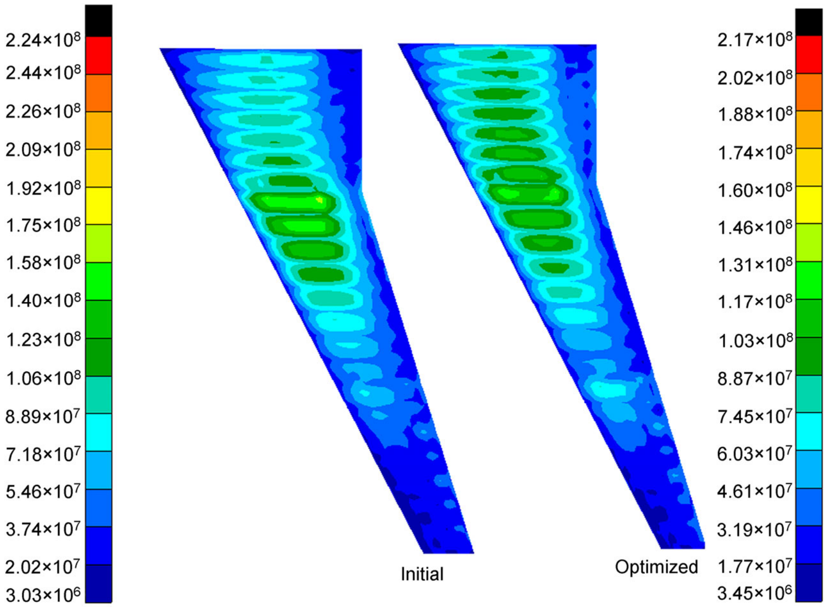

Figure 9 (Color online) Von Mises stress before and after optimization.

Table 3 Aerodynamic and structural characteristics comparison before and after optimization

	C_D	Mass (kg)	δ_{max} (Pa)
Initial	0.03023	2206.0	2.237×10^8
Optimized	0.02998	2117.6	2.166×10^8
DJS3	0.02995	2117.6	2.158×10^8

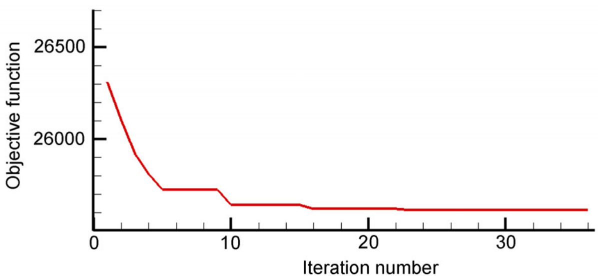

Figure 10 (Color online) Convergence history of the aero-structural optimization.

(2) An aero-structural optimization framework is established, in which RISM is used to evaluate the aerodynamic and structural performance. This optimization framework decreases the computational expense by four times compared with conventional optimization based on loosely-coupled static aeroelastic analysis.

(3) The wing-body configuration optimization verified the effectiveness of the proposed methodology, in which aerodynamic and structural performance are optimized simultaneously. It shows that the proposed methodology has great potential in aerodynamic/structure optimization, and it is especially suitable for the preliminary/detailed design of high-aspect-ratio aircrafts.

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