29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

EFFICIENT AERO-STRUCTURAL DESIGN OPTIMIZATION BASED ON HIGH-FIDELITY METHODS

ZUO YingTao*, GAO ZhengHong*, CHEN Gang**
*** National Key Laboratory of Aerodynamic Design and Research, Northwestern Polytechnical University, Xi' an, Shaanxi, 710072, China,**
**** State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi' an Jiaotong University, Xi' an, Shaanxi, 710049, China**

Keywords: *Aero-structural optimization; CFD/CSD; surrogate model*

Abstract

Traditional coupled multidisciplinary design optimization based on computational fluid dynamics/computational structure dynamics (CFD/CSD) aims to optimize the jig shape of aircraft, and static aeroelastic analysis is used to get the aero-structural performance. The huge computational expense hampered its application in engineering. Now we put forward an efficient methodology to predict the aero-structural performance of aircraft: reverse iteration of structural model(RISM), which is far more efficient than the conventional loosely-coupled aeroelastic analysis. A multidisciplinary design optimization framework based on RISM and surrogate model is proposed. Test show that RISM is four times faster than loosely-coupled aeroelastic analysis. A wing-body configuration was optimized by the proposed framework successfully, which shows the effectiveness of the proposed framework.

1 Introduction

Fluid-structure coupled numerical simulations are widely used in jig shape correction, model design before wind tunnel experiment and multidisciplinary design optimization in modern aircraft design today. Much aero-structural coupled design optimization framework is developed in the past decade. Many researchers have presented very successful applications of aero-structural coupled design optimization. Typical application includes the detailed wing optimization and winglet design in German aerospace center (DLR) [1], supersonic and hypersonic aircraft design etc[2].

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[3]. Some researchers developed effective optimization frameworks for aerodynamic/ structural design optimization. These frameworks include optimizations based on genetic algorithm and all kind of surrogate models[4-9]. After years of rapid development, the surrogate-based optimization entered a bottleneck period, and no breakthrough has been made in recent years. Many researchers construct complex multi-fidelity optimization framework to satisfy the various requirement of different phases of aircraft design[10-14]. 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[15-16], Maute[17], Fazzolari[18], Ghazlane[19], etc.

In all these researches the jig shape was parameterized and optimized, and static aeroelastic analyses is used 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. Aly[20] tried to avoid the time-consuming aeroelastic analyses. 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.

As we know that cruise shape of aircraft can be transformed into jig shape by jig shape correction, and we get aero-structural performance of the aircraft at the same time. Therefore, if we parameterize the cruise shape of aircraft, we may construct a novel optimization framework. All we have to do is to get the aero-structural performance of the aircraft efficiently.

The remainder of this paper is organized as follows: Section 2 describes the two high fidelity models adopted for the multidisciplinary 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

$$\frac{d}{dt}\int_{\Omega} Q dV + \int_{\partial\Omega} F \bullet \hat{n} dS = \int_{\partial\Omega} G \bullet \hat{n} dS \qquad (1)$$

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. Q is the set of conservative flow variables. F is the inviscid flux tensor, and 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[21].

Structural analysis is carried out by finite element analysis.

Data exchange between fluid and structure is very important in fluid-structure interaction (FSI). Many algorithms have been developed to transfer data between CFD and CSD models, which include infinite-plate spline (IPS), boundary element method (BEM), constant-volume tetrahedron (CVT), radial basis functions (RBF), etc.[22-25]. 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 multidisciplinary 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. Usually we need to call CFD and CSD solvers 5-10 times in this procedure, which is very time-consuming and inefficient. We get the mass, aerodynamic forces, maximum displacement and maximum stress of the cruise shape by static aeroelastic analysis.

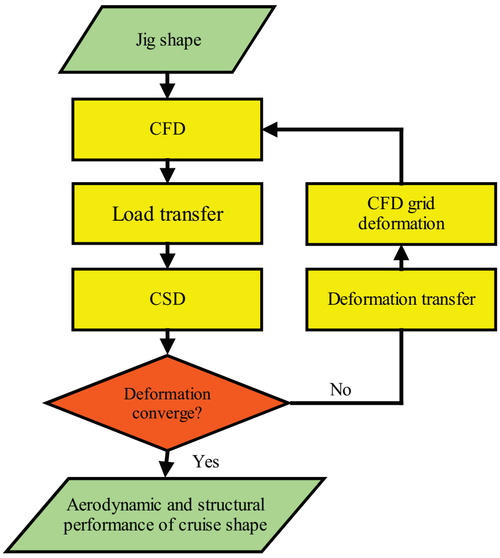

Fig. 1 Flowchart of typical static aeroelastic analysis

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, we need to get the jig shape corresponding to the cruise shape 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.

We adopted Aly's methodology[20] to get the jig shape at first. 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 $\boldsymbol{K}$ represents the stiffness matrix of the cruise shape, $\boldsymbol{X}$ is the unknown vector of the structural deformation, and $\boldsymbol{F}$ is 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 is not very precise. If we apply the aerodynamic load of cruise shape, etc., to the jig shape, we get the deflected jig shape. It ought 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].

It is notable that the jig shape deforms into the cruise shape under the forces including the aerodynamic load of the cruise shape at last. This prompts a way of using the aerodynamic 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 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.

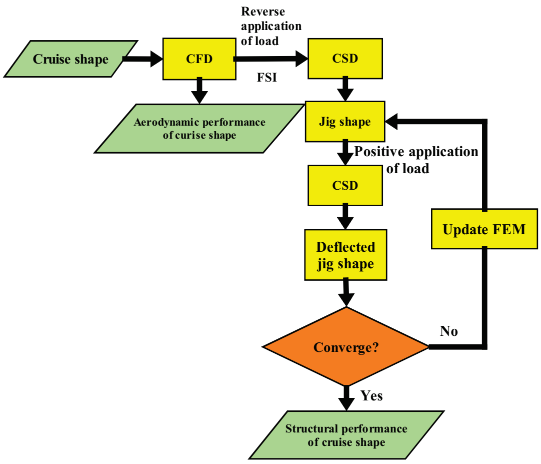

Fig. 2 Aero-structural analysis

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

$$K_{cruise}\Delta U_1 - F = 0 \qquad (2)$$

where K_{cruise} is the structural stiffness matrix of cruise shape, ΔU_1 is the structural displacement and 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:

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

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:

$$X_{s2} = X_{s1} + \Delta U_1 \quad (4)$$

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

$$\begin{aligned} K_{jig}\Delta U_2 - F &= 0 \\ X_{s3} &= X_{s2} + \Delta U_2 \end{aligned} \quad (5)$$

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 finite element mesh (FEM) of the deflected jig shape.

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

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

The essence of RISM is solving the following nonlinear equation:

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

where K is the structural stiffness matrix of jig shape, and it depends on the coordinate vector of 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.

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 four times at least 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 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 optimization is organized as follows.

(1) Initial samples are generated by Latin hypercube sampling method. The responses of these sample points are evaluated by the proposed aero-structural analysis methodology.
(2) Construct Kriging surrogate model based on the sample points and corresponding responses.
(3) Search the model to get the optimum by genetic algorithm. Validate the optimum by the proposed aero-structural analysis methodology.
(4) If the variation of objective function is small enough, stop; Otherwise the new results are added to the sample dataset, and go to step (2).

4 Testing and analysis

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 3(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[20].

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

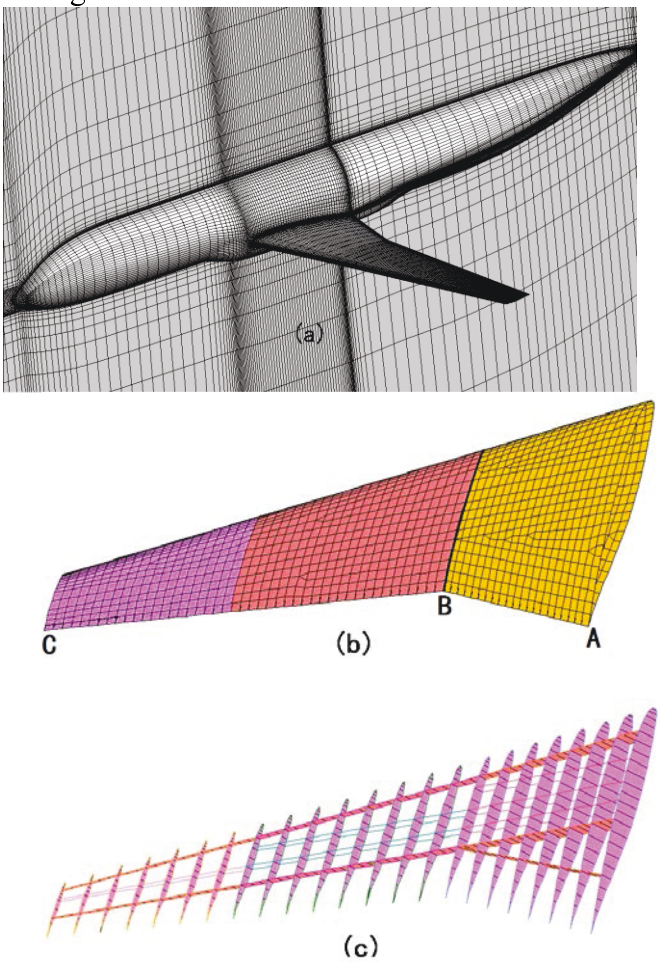

Fig. 3 CFD grid of wing-body configuration and wing structural model

4.1 Validation of RISM

RISM methodology is validated firstly. The deflected jig shape is named DJS1. The semispan of the aircraft is 17.02m. The maximum displacement of deflected jig shape compared with jig shape is 0.940m. The comparison of jig shape and cruise shape is shown in Figure 4. The maximum distance between the corresponding nodes of cruise shape and DJS1 is 0.001m. This means that these two FEM almost coincide. Figure 5 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 0.063m. The difference of von Mises stress is even larger.

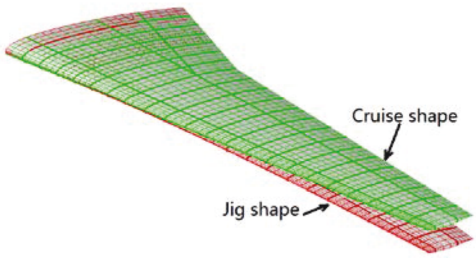

Fig. 4 Comparison of jig shape and cruise shape

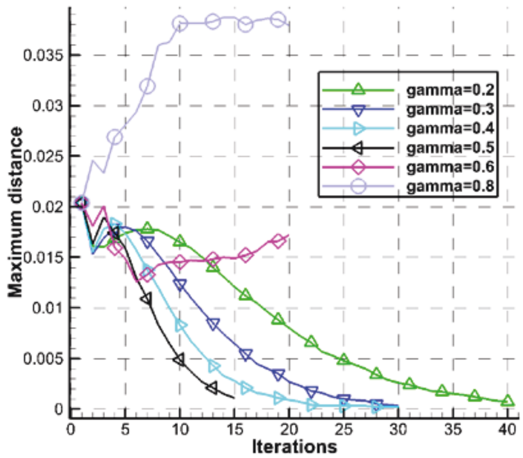

Fig. 5 Convergence history of RISM

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 6 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 0.948m. 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.

Table 1 Structural characteristic of the aircraft predicted by various methods

Prediction method	Maximum displacement, m	Maximum stress, Pa
Aly' method	0.877	1.820×10^8
RISM	0.940	2.237×10^8
Static aeroelastic analysis	0.948	2.249×10^8

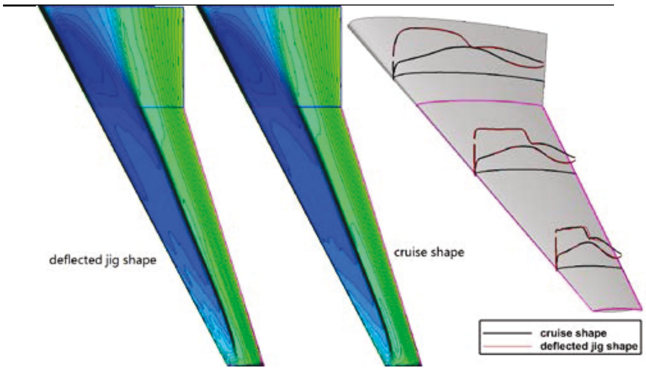

Fig. 6 Pressure contour of the cruise shape and the deflected jig shape

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

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-structural design optimization.

4.2 Aero-structural optimization

Wing section B in Figure 3(b) is parameterized. The wing root and wing tip section as shown in Figure 3(b) is used to control the start and end of deformation. Hicks-Henne function is used to parameterize the upper and lower surface of section B. 6 design variables are selected for the upper and lower surface of section B each.

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 9, and the total number of design variables is 21.

The objective is to minimize the drag and weight of the aircraft. Two constraints are enforced. One is that the lift must be constant, which means C_L is fixed. The other is that the maximum stress of material under cruise status cannot exceed a given value. 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:

$$\text{Min} \quad C_1 D + C_2 W$$

$$\text{s. t} \quad \begin{array}{l} C_L = 0.55 \\ \delta_{\max} < 2.3\times 10^8 \ P_a \end{array}$$

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 0.5 and C_2 to be 0.5 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. The aircraft is optimized by the former optimization framework, and the number of initial samples is 430.

The pressure contour of the aircraft and the sectional pressure distribution before and after optimization are shown in Figure 7. The von Mises stress comparison before and after optimization is shown in Figure 8. The aerodynamic and structural characteristics before and after optimization are shown in Table 3. As can be seen, a decrease of 12.4 aerodynamic counts of drag coefficient obtained after optimization with the mass of wing decreased by 6.48%. Shock was weaken after optimization. The shock will weaken further if we increase the number of parameterized wing section.

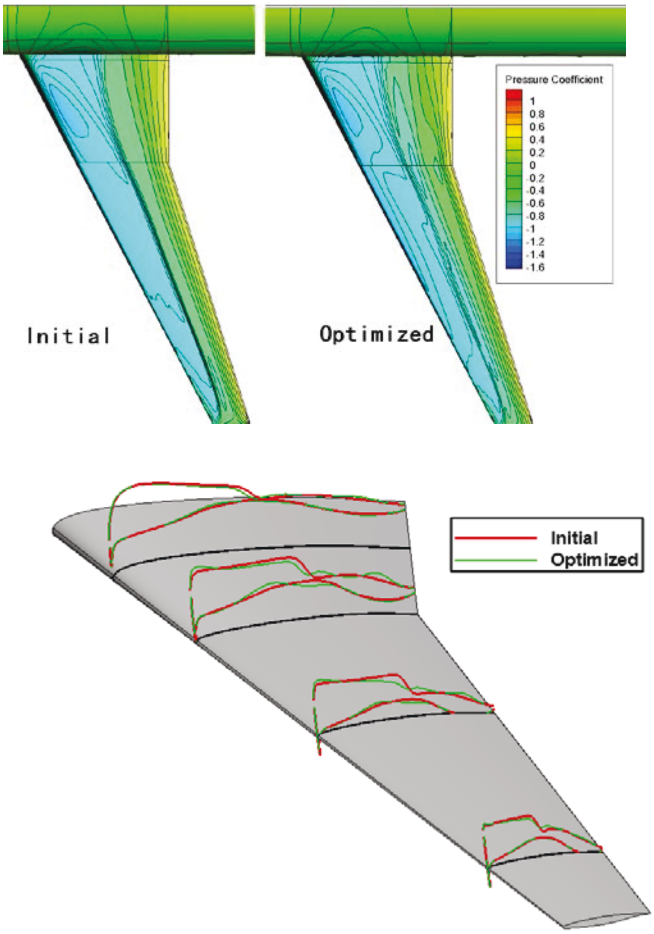

Fig. 7 Pressure contour and sectional pressure distribution comparison before and after optimization

Table 3 Aerodynamic and structural characteristics comparison before and after optimization

	C_D	*Mass*, kg	δ_{max}, P_a
Initial	0.03023	2206.0	2.242×10^8
Optimized	0.02899	2063.1	2.237×10^8

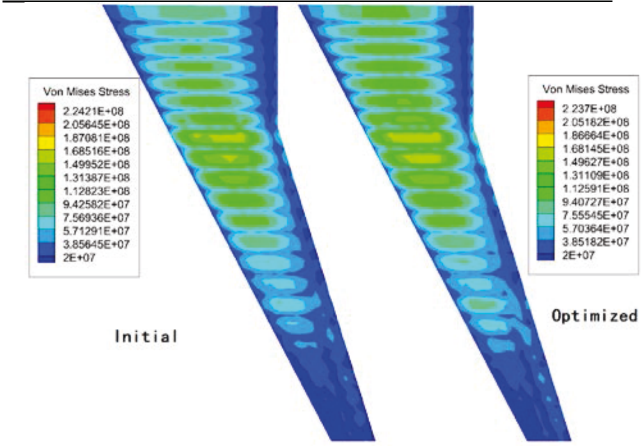

Fig. 8 Von Mises stress before and after optimization

The optimization efficiency can be improved by four times compared with the traditional multidiscipline optimization based on static aeroelastic analysis. The optimization calls 470 times of the CFD solver. This expense is much lower compared with that of the optimization based on genetic algorithm.

5 Conclusions

An efficient aero-structural performance prediction methodology is proposed in this paper. The efficiency is improved by four times at least compared with loosely-coupled static aeroelastic analysis. Test shows that the fidelity is almost the same as that of the loosely-coupled static aeroelastic analysis.

The aero-structural optimization framework based on surrogate model and RISM constructed in this paper is very efficient in multidisciplinary design optimization. Test shows that it decreases the computational expense by four times compared with conventional optimization based on loosely-coupled static aeroelastic analysis. All these show 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.

References

[1] Andrew S. N, Kroo I. Multidisciplinary considerations in the design of wings and wing tip devices. *Journal of aircraft*. Vol. 47, No. 2, pp 534-543, 2010

[2] Allison D L, Morris C C, etc. A multidisciplinary design optimization framework for design studies of an effient supersonic air vehicle AIAA 2012-5492

[3] Kim, Y, Jeon Y H, and Lee D H. Multi-objective and multidisciplinary design optimization of supersonic fighter wing. *Journal of aircraft*, Vol. 43, No. 3, pp 817-824, 2006.

[4] Coutu D, Brailovski V, etc. Aerostructural model for morphing laminar wing optimization in a wind tunnel. *Journal of aircraft*, Vol. 48, No. 1,pp 66-76. 2011.

[5] Park K H, Jun S O, etc. Reduced-Order Model with an Artificial Neural Network for Aerostructural Design Optimization. *Journal of aircraft,* Vol. 50, No. 4, pp 1106-1116, 2013

[6] Zill T, Ciampa, P D and Nagel B. Multidisciplinary design optimization in a collaborative distributed aircraft design system. *AIAA 2012-0553*.

[7] Rajagopal S, Ganguli R. Multidisciplinary design optimization of a UAV wing using Kriging based multi-objective genetic algorithm. *AIAA* 2009-2219.

[8] Nikbay M, Öncü L, and Aysan A. Multidisciplinary code coupling for analysis and optimization of aeroelastic systems. *Journal of Aircraft,Vol.* 46, No. 6, pp 1938-1945, 2009.

[9] Lian Y, and Liou M S. Aerostructural optimization of a transonic compressor rotor. *Journal of Propulsion and Power*, Vol. 22, No. 4, pp 880-888, 2006.

[10] Lehner S G, Lurati L B, Bower G C, et al. Advanced multidisciplinary optimization techniques for efficient subsonic aircraft design. *AIAA 2010-1321*.

[11] Piperni P, DeBlois A, and Henderson R. Development of a multilevel multidisciplinary-optimization capability for an industrial environment. *AIAA Journal*, Vol. 51, No. 10, pp 2335-2352, 2013.

[12] Cavagna L, Ricci S and Riccobene L. Structural sizing, aeroelastic analysis, and optimization in aircraft conceptual design. *Journal of Aircraft,* Vol. 48, No. 6, pp 1840-1855, 2011.

[13] Ghoman S S, Kapania R K, Chen P C, et al. Multifidelity multistrategy and multidisciplinary design optimization environment. *AIAA 2013-4672*.

[14] Liem R P, Mader C A, Lee E, et al. Aerostructural design optimization of a 100-passenger regional jet with surrogate-based mission analysis. *AIAA 2013-4372*.

[15] Martins, J R R A, Alonso, J J, Reuther J J. High-fidelity aerostructural design optimization of a supersonic business jet. *Journal of Aircraft*, Vol. 41, No. 3, pp 523-530, 2004.

[16] Kennedy G, Martins J R R A, Hansen J S. Aerostructural optimization of aircraft structures using asymmetric subspace optimization. *AIAA 2008-5847*.

[17] Barcelos M, Maute K. Aeroelastic design optimization for laminar and turbulent flows. *Comput Methods Appl. Mech. Engrg*. 2008; 197(19–20) : 1813-1832.

[18] Fazzolari A, Gauger N R, Brezillon J. Efficient aerodynamic shape optimization in MDO context. *Journal of Computational and Applied Mathematics*, Vol. 23, No. 2, pp 548-560, 2007.

[19] Ghazlane I, Carrier G, Dumont A, et al. Aerostructural adjoint method for flexible wing optimization. *AIAA 2012-1924*.

[20] Aly S, Ogot M, Pelz R, et al. Jig-shape static aeroelastic wing design problem: a decoupled approach. *Journal of Aircraft*, Vol. 39, No. 6, pp 1061-1066, 2002.

[21] Yoon S, Jameson A. Lower-upper symmetric-gauss-seidel method for the Euler and Navier-Stokes equations. *AIAA Journal*, Vol. 26, No. 9, pp, 1025-1026, 1988.

[22] Swift A, Badcock K J. Inter-grid transfer influence on transonic flutter predictions. *AIAA 2010-3049*.

[23] Badcock K J, Rampurawala A M, Richard B E. Intergrid transformation for aircraft aeroelastic simulations. *AIAA 2003-3512*.

[24] Sadeghi M, Liu F, Lai K L, et al. Application of three-dimensional interfaces for data transfer in aeroelastic computations. *AIAA 2004-5376*.

[25] Huang W, Lu Z L, Guo T Q, et al. Numerical method of static aeroelastic correction and jig-shape design for large airliners. *Science China Technological Sciences,* Vol. 55, No. 9, pp 2447-2452, 2012.

Contact Author Email Address

Yingtao Zuo: zuoyingtao@nwpu.edu.cn

Copyright Statement