Application of Fluid-Solid Couple on Multidisciplinary Optimization Design for Turbine Blade

JIA Zhi-gang[1,*], WANG Rong-qiao[2], HU Dian-yin[2], FAN Jiang[2], Shen Xiu-li[2]

[1] China aviation engine establishment, Beijing, 100028, China
[2] School of Jet Propulsion, Beijing University of Aeronautics and Astronautics, Beijing 100191, China
* Corresponding author: jia2001720@126.com

Abstract The multi-field coupled analysis, a higher precision, is an interaction effect among the fluid, the structure strength and the thermal on the turbine design. Considering the coupled effect in the multidisciplinary optimization design (MDO) could further excavate the design potential and improve the optimization precision on the turbine. Thus the paper firstly shows the automatic process of the fluid-solid closely coupled analysis method based on the ALE which would be the foundation of the turbine MDO. The comparison between the analysis result of the couple and the single discipline on the turbine blade proves the transdisciplinary influence each other. Based on kinds of the different precise analysis methods, this paper secondly puts forward the multiple-precision strategy in order to balance the cost and the precision on turbine MDO. This strategy studies the variable complexity method (VCM) which is improved by the two-point scale function and the periodic updating technology and three kinds of precise models including the fluid-solid closely coupled analysis, the single discipline analysis and the approximate equation. The strategy solves the difficulty of disciplinary decoupling and coordination by the collaborative optimization (CO) strategy. Finally, the new strategy could finish the turbine MDO with acceptable performance.

Keywords fluid-solid closely coupled analysis; multidisciplinary design optimization (MDO); variable complexity method (VCM); collaborative optimization (CO) strategy; turbine design;

1. Introduction

Turbine blade working in the environment of the high temperature, high pressure and high centrifugal force is a typical component involving the multidisciplinary and the multi-flied coupled design. The MDO as a new design idea could design complex structure by adequately exploring the interaction mechanism between disciplines [1]. The previous MDO established on the foundation of the discipline analysis and completed the design process through decoupling and coordination among disciplines. Thus, the accuracy of the discipline analysis is an important factor on the MDO.

The development of the fine design contributes to further excavate the design potential on the engine. A single disciplinary numerical analysis is not accurate enough to discover some exact design problem which would improve the performance. The coupled analysis [2, 3] is a main method to achieve a high precision which has been the goal pursued by engineer and academic on the turbine. The fluid-solid couple, a crossed discipline between the fluid and the solid, is particularly prominent on the turbine blade. Its feature is that the structure generates deformation under the action of the fluid load while this deformation in turn affects the flow field. Making clear the relationship of the fluid-solid couple is conducive to further excavate the design performance.

If the coupled analysis was applied on the MDO, it would provide the favorable safeguard of the numerical precision for the engine design. However, previous study has shown that the coupled analysis has a high cost and numerical noise which would be serious influence on MDO cost, even convergence. Recently, the blade has developed various precision methods, such as the approximate equation which is low precise, the single discipline analysis and the discipline coupled analysis. The characteristics of the low precision are low cost and low numerical noise. How to organize these different accuracy analytical methods and fully express their advantages is a key content on greatly increasing the efficiency and accuracy of the blade MDO. The variable complexity modeling (VCM)

[4] could manage various models so that it could balance the cost and the precision of the MDO [5], and get a feasible optimal solution and avoid numerical noise. Nevertheless, the VCM also exist some shortage in the organization, so some improving methods are required.

Recently the MDO has made a great progress in some technology, but a lot of theory and methods which still stay in academic research stage without verification on complex engineering system design could have distance with the practical application. Therefore, this paper, in view of the aero-engine turbine and the high precise coupled analysis, will fully discuss the MDO method of the complex structure, which not only has very important significance and challenging but also provides certain technical support for the development of aero-engine.

2. Turbine Fluid-Solid Coupled Analysis

2.1. ALE Problem of Fluid-Solid Couple

For the coupled problem, the most difficulty lies in the unified coordinate system and the coordination of two phases interface. The Solid habits using the Lagrange coordinate system with a view to the particle, while the fluid uses the Euler coordinate system with a view to the space point. The descriptive differences could not be distinguished on a little movement problem, but is very complicated for big movement and nonlinear problem. The ALE (Arbitrary Lgrangian-Eulerian) method which Hirt puts forward to describe the free liquid in 1974 has been widely used [6]. It provides an efficient way connecting the Laplace system in solid with the Euler system in fluid. The ALE coordinate system could move in the space motion by any speed. If its velocity is zero, that is Euler system. If the speed equals to the particle velocity, that is namely the Laplace system. Thus the ALE coordinate system provides a unified description for two kinds of coordinate system.

This paper describes the fluid field in the ALE. The spatial domain uses the finite element discrete format, while the Navier-Stokes equation adopts the substep calculation format in the time domain. The fluid-solid closely coupled based on the ALE can combine the ANSYS with the CFX to complete iterative computation. When they solve in sequence, the interface need transfer the pressure from the fluid to the solid, and then transfer the displacement to fluid. This method considers the interaction between fluid and solid, so the accuracy is relative higher.

2.2. Dynamic Grid Technology and Coupled Step Settings

Because of the moving interface, the discrete equation of the fluid field must allow the grid mobile and the grid deformation. There are two kinds of the way [7-10]. The first one is named mesh fairing method dealing with the small mobile. This operation pulls and extrudes the grid in a small range displacement. That could be realized by solving the Laplace's equation. If the grid deformation is serious, the mesh fairing method is not enough to provide the high quality grid. In other case, the new grid must be established in maybe different grid topology. The variable value will be interpolated to the new nodes next time step. Because the grid nodes are inconformity before and after remeshing, the interpolation inevitably would produce the error. The remeshing cost is huge for hundreds of thousands nodes, so the efficiency could drop. Then, if the deformation is not a lot, for example that the maximum deformation in this paper is less than 1.4 mm (analysis data), the small-scale coupled timestep could solve the dynamic grid problem with the first method. Every coupled variable transfers more smoothly by the small-scale coupled timestep.

Usually, a blade employs the corresponding period of the first order natural frequency as the total timestep. The first order natural frequency is 723.522Hz. Its corresponding period is 0.00138s. Then this value is discrete for 10 steps as the coupled sub-timestep. The total time of the solid analysis and the fluid analysis should be same as the coupled time.

2.3. Process of Fluid-Solid Coupled Analysis Based on ALE

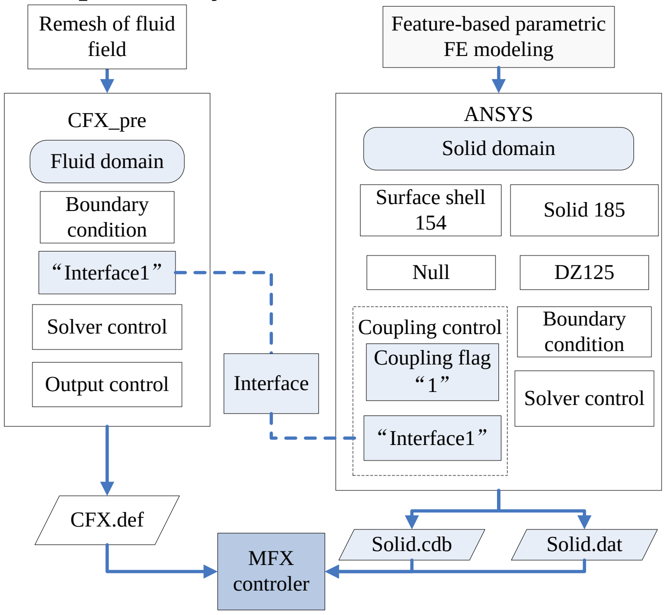

Figure.1 Process of the fluid-solid closely coupled analysis

Considering the inheritance of the analysis method, the paper establishes the flow of a fluid-solid closely coupled analysis on the turbine blade shown in figure 1, when the method of the parametric FE modeling based feature solves remeshing on the solid domain. The solid domain uses the ANSYS, while the fluid domain employs the CFX. The research process is steadily forward when every solver gets convergence. The mesh fairing method solves the mesh move. The coupled control does not only solve the conversion between the Eulerian coordinate system and the Lagrange coordinate system, but also transfers the pressure and the solid displacement. The MFX controller links solution files of two domains. The CFX.def contains fluid domain solver, while the solid domain file is divided into the model file (Solid.cdb) and the coupling file (Solid.dat). Finally, a batch is employed to call for each module of the process.

3. MDO technologies

The basic idea of the VCM [11] is: how to effectively use various precise models and bring the feasible solution based on the less cost. The traditional VCM mainly concentrated in both of the high and low precise analysis. The low precise model could improve the optimization efficiency, while the high precise analysis is responsible for introducing the correction factors which would enhance the precision of the results from the low precision during the cycle. Meanwhile, the correction factor is updated after several optimization iterations called interval method [12]. Thus it could be seen that the traditional VCM mainly includes two kinds of precision, the correction factor and the interval method. The paper will modify these three aspects so as to enhance the model management ability and adapt the higher precise method.

3.1. Various precise models

Set x as design variable. $f_{\mathrm{h}}(x)$ indicating the response of the coupled analysis in this paper is the high precise results; $f_{\mathrm{l}}(x)$ on behalf of the single discipline analysis response is the moderate accuracy analysis results; $f_{\mathrm{r}}(x)$ is the result of the response surface method belong to the low precise model. First of all, the medium accuracy analysis $f_{\mathrm{l}}(x)$ computes design points picked out by DOE, and the initial correction factor corrects them as $\tilde{f}_{\mathrm{h}}(x)$. This group of data could construct the initial optimization object and constraints, $f_{\mathrm{r}}(x)$, which would be used in optimization cycle; a correction factor is get by contrasting the high precise analysis $f_{\mathrm{h}}(x)$ with the medium precise analysis $f_{\mathrm{l}}(x)$, and the correction factor could be updated in the optimization process.

3.2. Periodic Updating Method

The correction factor in the traditional VCM could be updated once in several times cycle on the interval method. This method reduces the calling number of the high precise model on the optimization, so it does not only ensure the accuracy and also the efficiency. However, the interval method is often lack of rationality in the search space. For example, the difference between high and low precise analysis could not be constant in design space. When the difference tends to perhaps stable, the interval should be adopted large. When the difference has great fluctuation in the certain design space, the interval may be small. Therefore, the constant interval could not meet the fact. Therefore, it is worth studying problem how to properly use the high precise model to reasonable correct the low precise model.

This paper shows a new method called the periodic updating method. When the initial approximate function achieves convergence, the variable records as x_1^*. Meanwhile, the correct factor could be computed, when $f_{\mathrm{h}}(x_1^*)$ and $f_{\mathrm{l}}(x_1^*)$ is obtained by two kinds of precise analysis. New $\tilde{f}_{\mathrm{h}}(x_1^*)$ would be get by correct factor and added to the previous database. Then the approximation function would be reframed by the least square method from the updated database. The correct function and the approximate function reframed synchronously after the inner convergence provides a relative better time calling the high precise model in the periodic updating method.

3.3. Two-Point Scale Function

The correct method of $f_l(x)$ is called the scale function. Presently, the kinds of the correct factor have the additive factor and the multiplication factor, as well as their high order form, so the scale function are often divided into the addition scale function and the multiplication scale function. The value of $f_h(x_0)$ and $f_l(x_0)$ is obtained at the initial point x_0. The formula (1) could get a constant addition factor. The subscript "0" means the initial. The multiplication factor is as formula (2):

$$\alpha(x_0) = f_h(x_0) - f_l(x_0) \qquad (1)$$

$$\beta(x_0) = \frac{f_h(x_0)}{f_l(x_0)} \qquad (2)$$

The result of the approximate function will be corrected as $\tilde{f}_h(x)$ in the loop. The approximation of the $f_h(x)$ is expressed as the formula (3) and (4) at its design point x. The $\tilde{f}_h(x)$ obviously contains the information of the high accurate analysis and simplifies calculation process by the approximation model. $\tilde{f}_h(x)$ represents the data to construct the approximation function.

$$f_h(x) \approx \tilde{f}_h(x) = f_l(x) + \alpha(x_0) \qquad (3)$$

$$f_h(x) \approx \tilde{f}_h(x) = f_l(x)\beta(x_0) \qquad (4)$$

The addition scale function and the multiplication scale function do not make the full use of the high precise numerical results in the whole optimization process. They use only the high precise analysis results of a point. The previous high precise analysis result is difficult to reflect in the subsequent scale function. This paper introduces the two point scale function which combines the multiplication factor and the additive factor. At the initial point x_0, the two-point scale function displays for the formula (5); similarly, the scale function is formula (6) at x_1^*. α_1 and β_1 is solved from the formula (5) and formula (6) simultaneous as formula (7).

$$f_h(x_0) = \beta_1 f_l(x_0) + \alpha_1 \tag{5}$$

$$f_h(x_1^*) = \beta_1 f_l(x_1^*) + \alpha_1 \tag{6}$$

$$\begin{aligned} \beta_1 &= \frac{f_h(x_1^*) - f_h(x_0)}{f_l(x_1^*) - f_l(x_0)} \\ \alpha_1 &= f_h(x_1^*) - \beta_1 f_l(x_1^*) \end{aligned} \tag{7}$$

Accordingly, when the i th approximation function achieves convergence in inner loop, the $f_h(x_i^*)$ and $f_l(x_i^*)$ is obtained by calling the high and medium accuracy analysis at the design point x_i^*. The optimal solution x_{i-1}^*, the corresponding $f_h(x_{i-1}^*)$ and $f_l(x_{i-1}^*)$ could be also gain in the $i-1$th inner loop. Therefore the α_i and β_i could be list in the formula (8) and (9) :

$$\begin{aligned} f_h(x_{i-1}^*) &= \beta_i f_l(x_{i-1}^*) + \alpha_i \\ f_h(x_i^*) &= \beta_i f_l(x_i^*) + \alpha_i \end{aligned} \tag{8}$$

$$\begin{aligned} \beta_i &= \frac{f_h(x_i^*) - f_h(x_{i-1}^*)}{f_l(x_i^*) - f_l(x_{i-1}^*)} \\ \alpha_i &= f_h(x_i^*) - \beta f_l(x_i^*) \end{aligned} \tag{9}$$

Where α_i is the additive correct term, and β_i the multiplicative correct term. The two-point scale function inherits the former and later value of the high precise results, and need not calculate the additional derivative information. Thus the computational efficiency and precision are ensured simultaneously. Therefore, before the start of the $i+1$th inner loop, the original data will be corrected in accordance with the formula (10).

$$\tilde{f}_h(x_i^j) = \beta_i f_l(x_i^j) + \alpha_i \tag{10}$$

Where i stands for the number of inner loop executed; $j = 1 \cdots n$, n is the total number of sampling point. Then the value of $\tilde{f}_h(x_i^j)$ $j = 1 \cdots n$ could construct the approximate function $f_R(x_{i+1})$ of objects and constraints in the $i+1$th inner loop by the least-squares regression method.

3.4. Multiple-Precision Optimization Strategy

The collaborative optimization (CO) strategy [13, 14] need usually call a large number of discipline analyses. That means very expensive cost. Because the extra compatible constraint is optimization target in subsystem layer, the cost further increases. The CO efficiency has been improved by the approximation method [15], which is a good solution for the interdisciplinary relatively independent. However the inherent couple of the turbine blade does not reflected in a previous study. The discipline coupled analysis stands for the development of the high precise numerical method. Compared with the single discipline analysis, the closely coupled analysis need consume more cost.

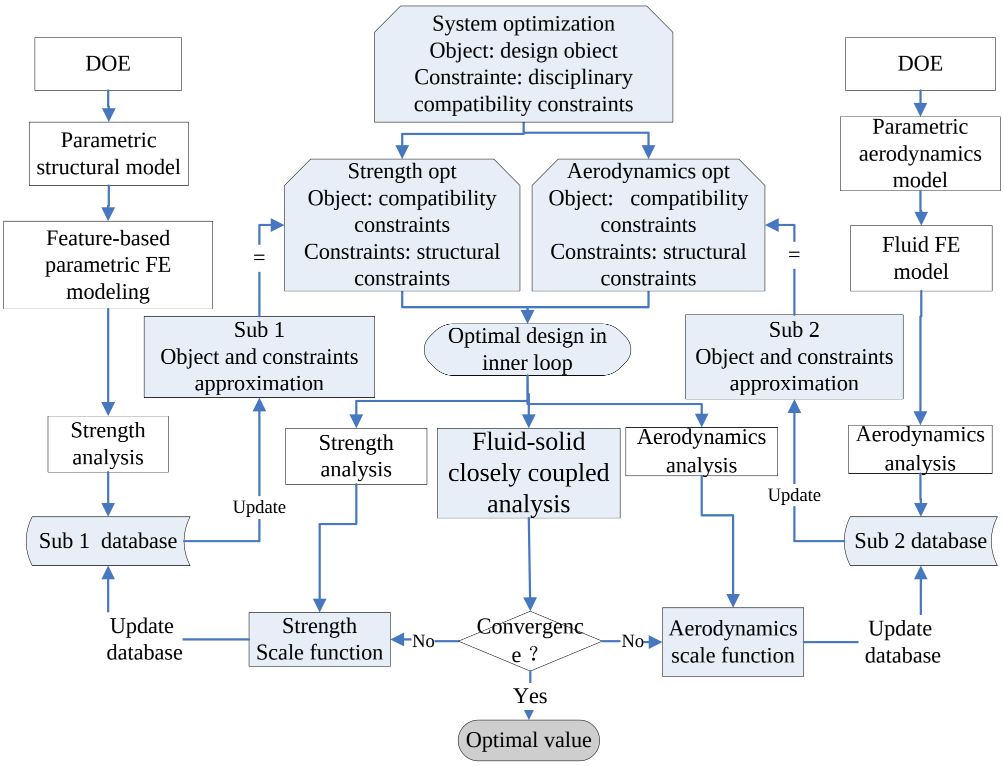

Figure.2 Multiple-precision optimization strategy

The figure 2 shows the multiple-precision optimization strategy which is the CO strategy referring the couple on the turbine blade MDO. This strategy will employ the coupled analysis into the CO strategy by using VCM technology. The way does not only improve the precision, but also makes the optimization results with the higher feasibility. The system level optimizer connects two sub-system optimizers which are used for processing the structure strength optimization and the fluid optimization. The database of the discipline 1 and discipline 2 contains their discipline analysis response and the corrected result at every DOE points. The object and constraint function in the sub-system optimizer is gain by the least square method at the database. The characteristic of fig.2 is nesting a CO strategy in the systemic loop. The optimal value of the CO will accept the aerodynamics analysis, the structure analysis and the flow-solid closely coupled analysis. The former two belong to the medium precision analysis. The latter's response data provides the scale function for the former two. Therefore the CO strategy is skeleton. The various precise methods are the core, and the VCM is the organization mode joining each element. The difference value of the high precision analysis, $f_{\mathrm{h}}(x_{i+1}^{*})-f_{\mathrm{h}}(x_{i}^{*})\leq 10^{-3}$, is less than 10^{-3} as the convergence criterion.

4. Coupled Analysis and MDO on the turbine blade

4.1. Model Parameters

The structure includes a shroud and a blade whose parameters are shown in figure 3 [16]. The nine shroud parameters are empirically chosen in this optimization, while this paper chooses six blade parameters which are the axial length (DZ_1, DZ_2 and DZ_3) and installation angle (γ_1, γ_2 and γ_3) on three sections of the hub, middle, and tip are blade parameters, as shown in fig.4. They have more influence on the aerodynamic performance. Constructing approximation of the fluid discipline needs at least 28 DOE points for the aerodynamics analysis. The approximate equations of the structure discipline need at least 136 DOE points. Design variables are $X=\{X_1, X_2\}$, including:

$$
\begin{aligned}
X_1 &= \{x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}\} \\
X_2 &= \{D_{Z1}, D_{Z2}, D_{Z3}, \gamma_1, \gamma_2, \gamma_3\}
\end{aligned}
\qquad (11)
$$

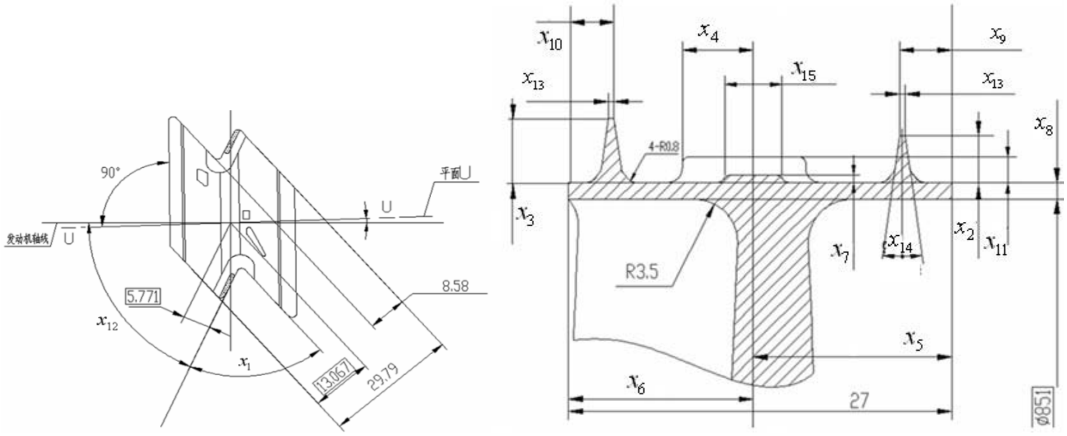

Figure.3 Parameters of shroud

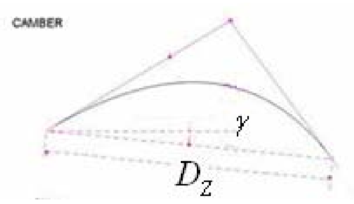

Figure.4 Parameters of a section

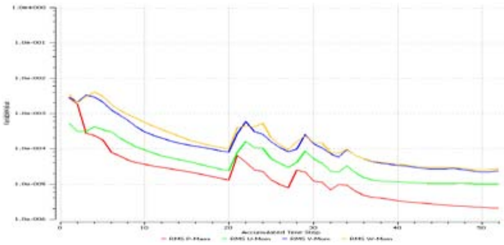

Figure.5 Convergence process of the close coupled field on the standard working speed

4.2. Result Analysis of Coupled Calculation on Turbine Blade

Fig.5 shows the convergence curve of the fluid-solid closely coupled analysis at the standard working speed on turbine blade. The result of the steady state aerodynamics calculation conducts the initial condition for the coupled analysis. This way is in favor of convergence. It could be seen that several important indexes of the fluid field has reached convergence after three big shocks which respectively represent the process transferring three times of coupled data. The three shocks also reveal that the distortion of the structure has great influence on the flow field.

Table.1 Result contrast between the closely coupled analysis and the aerodynamics analysis

	Max temperature(K)	Min temperature（K）	Max pressure（Pa）	efficiency
Aerodynamics	1332.11	853.625	603182	87.4964
Closely coupled	1339.07	889.327	599312	88.1004
Absolute error	6.96	35.702	-3870	0.604
Relative error	0.5225%	4.1824%	-0.6416%	0.6903%

Table 1 shows the calculation results of the closely coupled field and the single fluid field at the work speed. It could be found that the coupled field has the higher isentropic efficiency and the mass flow. The statistical results show the difference of minimum temperature is 35.702 °. The relative error of the maximum pressure and max temperature is respectively 0.64% and 0.5225%.

Further comparing the stress and displacement before and after couple, table 2 gives the calculation results of the maximum displacement and maximum stress under various kinds of loads. Additionally, the centrifugal load and the aerodynamic load are separately considered. The aerodynamics load (A) is from the closely coupled analysis. The maximum stress of the closely coupled analysis is 593.548MPa located in the blade root trailing edge. In the aerodynamics load, the maximum stress is 43.016 MPa, which is much less than the value, 552.697MPa, under the centrifugal load condition. From magnitude, the displacement and the stress in the coupled calculation is equivalent to the total effect of the centrifugal load and the aerodynamics load.

Table.2 Contrast of the maximum displacement and stress under different load condition

Load type	Max Von Mises stress（MPa）		Max displacement（mm）	
	blade	shroud	blade	shroud
Centrifugal load	552.697	433.24	1.348	1.5348
Aerodynamics load（A）	43.016	——	0.09335	0.09916
Centrifugal load +（A）	593.548	435.944	1.411	1.613

4.3. Optimization Model of Turbine Blade Based on CO Strategy

The turbine blade adopts the DZ125 materials. The material requires that the equivalent stress is not more than 75%$\sigma_{0.1}$, the maximum stress of the joint is not more than 60%$\sigma_{0.1}$, and the contact stress is less than the allowable pressure stress. The temperature of the material is restricted to 1273.5K and the mass flow (mf) limited in range $[102.5,112.5](kg.s^{-1})$. Additionally the radial tip elongation is not more than 0.01m. Those are constraint condition, definited $Y=\{Y_1,Y_2\}$, where Y is the system response value, Y_1 the response value of the structure strength discipline, Y_2 the fluid discipline response value, as formula (12). The object function adopts the weighted sum of the isentropic efficiency and the total mass in the formula (13):

$$\begin{aligned}&Y_1=\{dx_{tip},\sigma_{shroud},\sigma_{chamfer},\sigma_{blade},\sigma_{contact}\}\\&Y_2=\{mf,T\}\end{aligned}\qquad(12)$$

$$\begin{cases}F(X)=W_1/\eta(X)+W_2*m(X)/m_0(X)\\m(X)=m_1(X)+m_2(X)\\m_0(X)=m_{10}(X)+m_{20}(X)\end{cases}\qquad(13)$$

Where $\eta(X)$ is the isentropic aerodynamics efficiency function, $m(X)$ the quality function of the shrouded blade, $m_0(X)$ the initial model quality of the shrouded blade. The subscript 1 is the blade and the subscript 2 is shroud. W_1 and W_2 is the weighted factor, respectively taking 0.7 and 0.3. The MDO model of the turbine shrouded blade can be wrote as formula (14).

$$\begin{cases}find:\ X\\\min F(X)=W_1/\eta(X)+W_2*m(X)/m_0\\s.t.\quad g_1=dx_{tip}-0.01\le 0\qquad g_5=\sigma_{contanct}-173.0\le 0\\g_2=\sigma_{shroud}-645.5\le 0\qquad g_6=mf\in[78.5,80.5]\\g_3=\sigma_{chamfer}-516.4\le 0\qquad g_7=T-1273.5\le 0\\g_4=\sigma_{blade}-697.0\le 0\qquad \mathrm{X}\in[X^l,X^u]\end{cases}\qquad(14)$$

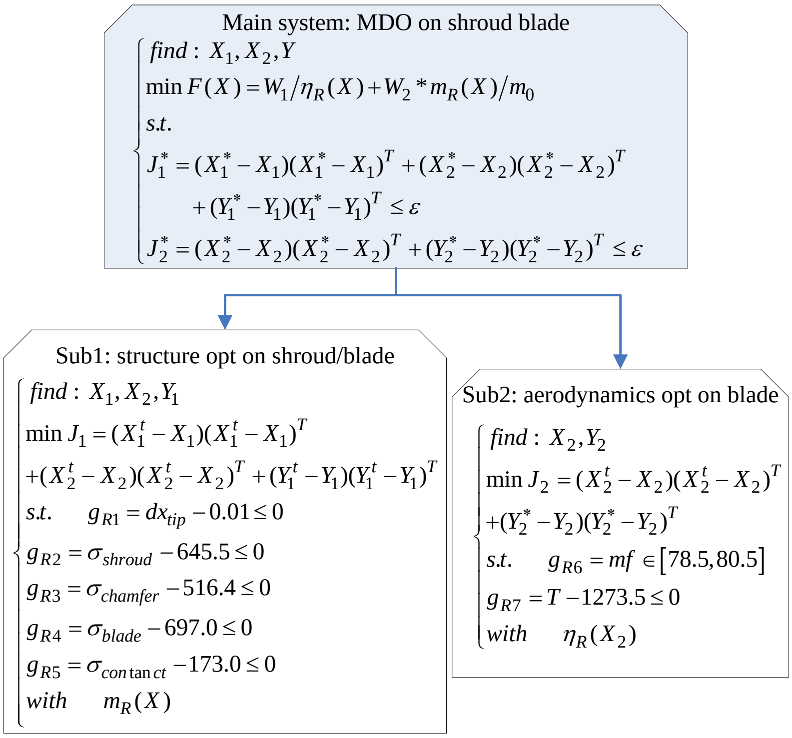

Figure.6 Optimization algorithm structure based on the CO strategy

Figure 6 shows the optimization algorithm structure of the blade MDO based on the CO strategy. $g_{Ri}, i = 1 \cdots 7$ stands for the approximate function. $m_R(X)$ and $\eta_R(X)$ respectively represent two sub-system targets. ε is the permissible error of compatible constraint taking $\varepsilon = 10^{-3}$.

4.4. Optimization Results Analysis

The paper establishes the multiple-precision optimization strategy. Present three kinds of analysis model on turbine blade have embodied in the CO framework by the VCM methods. The figure 7 describes shape changes in the blade root, middle and tip. Table 3 is the numerical response contrast. Under the constraints, the total mass drops 6.68% and the blade efficiency increases 5.55%.

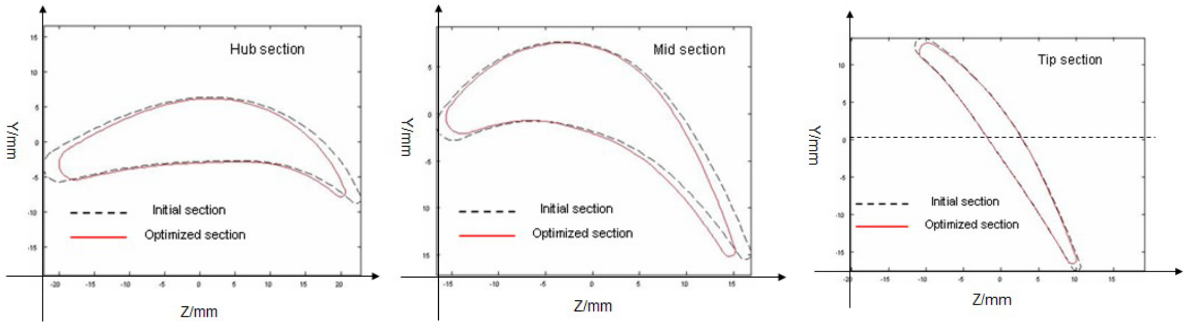

Figure.7 Compared shapes before and after optimization at the hub, mid and tip section

Table 4 shows the optimization cost of the shrouded blade. "——" represents none in the table. Because the approximate function runs quickly, the cost of the inner loop is not easy to statistics indicated with "......". From the table, major time consumption comes from the DOE, the calling number and the number of the inner loop, total of which is 7163 minutes (518+1665+4980), while the approximation function and updating overall occupies only 38 minutes (7201-7163). It shows that the approximate function could greatly improve the efficiency in optimization process. Because the fluid-solid closely coupled analysis costs very huge, the calling number directly affects the efficiency. The time consumption from the high precise analysis is about 4980 minutes, accounting for nearly 70% of the total time cost. The method pays some cost. However for accurate turbine blade design, the high precise numerical method is indispensable on the optimization. Considering the efficiency, the paper calculates the correction factor to correct the approximation function so that the optimal value could have the high precision and high feasibility.

Table.3 Result before and after optimization on shrouded blade

$Y=\{Y_1,Y_2\}$	Constraints	Initial value	Optimal value	Effect
Strength constraints (Y_1)	d_{xtip} /MPa	0.0035	0.00295	-15.71%
	σ_{shroud} /MPa	435.024	450.3	3.51%
	σ_{chamfer} /MPa	270.125	295.364	9.25%
	σ_{blade} /MPa	593.141	575.364	-3.00%
	σ_{contact} /MPa	80.1019	105.673	+31.92%
Aerodynamics constraints (Y_2)	$m_f\ /\ kg.s^{-1}$	107.363	106.825	-0.50%
	T /K	1234.86	1187.75	-1.3%
	Object	Initial value	Optimal value	Effect
Strength object	$m(X)$/g	203.27	189.7	-6.68%
Aerodynamics object	$\eta(X)$	0.874964	0.92353	5.55%
Weight object	$F(X)$	1.100	1.0379	-5.65%

Table.4 Cost of multiple precision MDO strategy on turbine

Discipline	Analysis type	Model accuracy	DOE number	Calling number	Cycling number	Cost (min)
Strength	Strength analysis	medium	136	8	——	518
	Approximation	low	——	——	9528	······
Aerodynamics	Aerodynamics analysis	medium	28	8	——	1665
	Approximation	low	——	——	6864	······
Couple	closely coupled analysis	high	——	9	——	4980
——				Total cost		7201

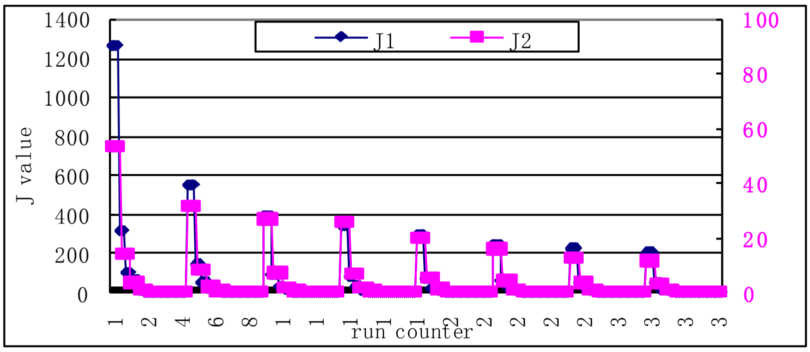

Figure.8 Convergence curve of the Compatibility constraints J_1^*, J_2^* on the system layer

The compatibility constraint is an important index measuring convergence in the CO strategy. Fig.8 shows the convergence curve of the compatibility constraint J_1^*, J_2^* during the system layer. J1 represents J_1^* and J2 represents J_2^*. Because the value has huge difference, two kinds of longitudinal axis are adopted. The eight convergence phases show that the whole process constructs and updates 8 times of the approximate function. Because the $i+1$th optimization starts with the optimal value of the ith optimization, the J_1^* and J_2^* of the $i+1$th optimization is obviously smaller than them in the ith optimization (initial value in the $i+1$th time is much better), and converges faster. Each value in the database is revised by the high precise analysis in inner loop. Thus the approximation function has greater change (see figure 8). That is the main reason that this strategy needs more internal optimization, namely calling more number of the high precise analysis.

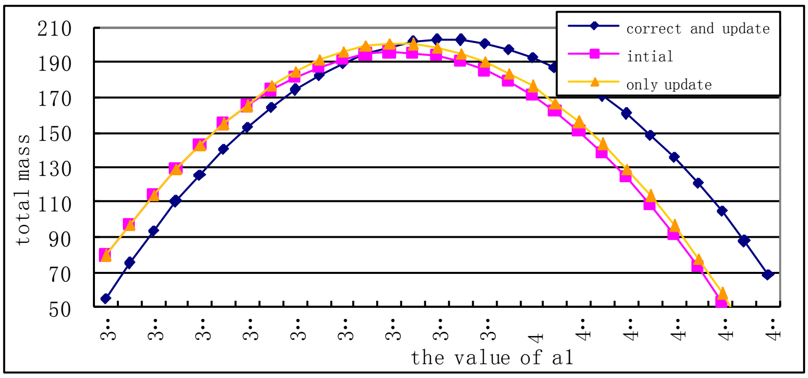

Figure.9 Initial target approximate function, the 8th corrected and updated, and only updated target approximate function at x_9

Figure 9 shows the initial target approximate function (C1), the 8th corrected and updated approximate function (C2), and 8th only updated target approximate function (C3) at x_9. The C2 parabolic axis of symmetry has obviously offset in relative to the C1 curve, while the C3 has the almost same axis with the C1, but its parabolic top is little different. The change of the parabolic axis just comes from the high precise analysis result which corrects the lower precise analysis.

Conclusion

This paper firstly explores the current fluid-solid coupled algorithm on the turbine design. According to the principle of the ALE with existing commercial software, the dynamic grid technology of the blade fluid domain is realized by the small coupled step length and the mesh fairing method. Then combining with the previous remesh technology, the paper establishes the process of the turbine blade fluid-solid closely coupled analysis based on the ALE.

Further the multiple-precision optimization strategy is established. The high precision of the fluid-solid coupled analysis should be applied to the turbine blade MDO to improve the design accuracy. Because of the huge cost of the high precise analysis, this paper studies the VCM methods from three aspects which are various precise models, the periodic update and the two point scale function in order to improve the efficiency and accuracy of the optimization. The VCM introduces the high, medium and low precise model into the MDO. The method of the periodic update properly employs the high precision model to reasonable correct the low precision model. The two point scale function adequately utilizes the high precise analysis of the optimization process to correct the result of the low precise model.

Finally, comparing the calculated results before and after coupling, the paper detailedly analyses the influence of disciplinary couple. Introducing the structural displacement, the total efficiency of the coupled field is slightly higher than single fluid analysis; the aerodynamic force is much smaller relative to the centrifugal force, the maximum equivalent stress of the closely couple is probably equivalent to the sum of individual effects of the aerodynamic force and centrifugal force. Additionally, the paper lists the optimal value on the multiple-precision optimization strategy. The result ensures the precision and efficiency of the turbine blade MDO after the optimization method only calls nine times of the high precise analysis.

References

[1] WANG Rong-qiao, JIA Zhi-gang, FAN Jiang, HU Dian-yin，Shen Xiu-li. Hexahedral mesh regeneration method for MDO on complex aero-engine components[J]. Journal of Aerospace Power, 201109, 26(9): 2032-2038. （in Chinese）

[2] Hirt C. W., Amsden A. A., Cook J. L. An Arbitrary Lagrangian-Eulerian Computing Method for All Flow Speeds[J]. Journal of Computational Physics. 1974, 14(3): 227-253.

[3] Carstens V., Kemme R., Schmitt S. Coupled Simulation of Flow-Structure Interaction in Turbomachinery[J]. Aerospace Science and Technology. 2003, 7(4): 298-306.

[4] Singh G., Grandhi R. V. Mixed-Variable Optimization Strategy Employing Multifidelity Simulation and Surrogate Models[J]. AIAA Journal. 2010, 48(1): 215-223.

[5] Baker M. L., Munson M. J., Alston K. Y., et al. Integrated Hypersonic Aeromechanics Tool (IHAT)[R]. Norfolk, Virginia: 12th AIAA International Space Planes and Hypersonic Systems and Technologies. AIAA paper 2003-6952. 2003.

[6] Hirt C. W., Amsden A. A., Cook J. L. An Arbitrary Lagrangian-Eulerian Computing Method for All Flow Speeds[J]. Journal of Computational Physics. 1974, 14(3): 227-253.

[7] Dinh Q. V., Mantel B., He J. W. A Cartesian Grid Finite Element Method for Aerodynamics of Moving Rigid Bodies[J]. 1992, 1: 883-890.

[8] Grüber B., Carstens V. Computation of the Unsteady Transonic Flow in Harmonically Oscillating Turbine Cascades Taking into Account Viscous Effects[J]. Journal of Turbomachinery. 1998, 120(1): 104-111.

[9] Richter, Leyland R., Penelope L. Precise Pitching Airfoil Computations by Use of Dynamic Unstructured Meshes[R]. AIAA 24th fluid dynamics conference. AIAA 93-2971. 1993.

[10] Blom F. J., Leyland P. Analysis of Fluid-Structure Interaction by Means of Dynamic Unstructured Meshes[J]. Journal of Fluids Engineering. 1998, 120: 792.

[11] Kaufman M., Balabanov V., Giunta A. A., et al. Variable-Complexity Response Surface Approximations for Wing Structural Weight in HSCT Design[J]. Computational Mechanics. 1996, 18(2): 112-126.

[12] Macmillin P. E. Trim, Control, and Performance Effects in Variable-Complexity High-Speed Civil Transport Design[D]. Virginia Polytechnic Institute and State University, 1996.

[13] Shanno D. F. Conditioning of Quasi-Newton Methods for Function Minimization[J]. Mathematics of Computation. 1970, 24(111): 647-656.

[14] Goldfarb D. A Family of Variable Metric Methods Derived by Variational Means[J]. Mathematics of Computation. 1970, 24(109): 23-26.

[15] Sangook J., Young-Hee J., Rho A. J., et al. Application of Collaborative Optimization Using Response Surface Methodology to an Aircraft Wing Design[R]. Albany, New York: 10th AIAA/ISSMO Multidisciplinary Analysis and optimization conference. AIAA 2004-4442. 2004.

[16] WANG Rong-qiao, JIA Zhi-gang, Yang Jun-jie, HU Dian-yin, FAN Jiang, Shen Xiu-li. Study on disk and blade design based on multi-layer optimization strategy. Journal of Aerospace Power. 201206, 27(6): 1201-1209. （in Chinese）