Multidisciplinary Design Optimization of Turbine Disks Based On ANSYS Workbench Platforms

Qi Xiaodonga,*, Shen Xiulib

aAVIC Commercial Aircraft Engine Co. Ltd., Shanghai, China
bSchool of Jet Propulsion, BUAA, Beijing, China

Abstract

The design of aero engine turbine disks, which are working under high thermal and centrifugal loads, is an interactive and multidisciplinary process that includes several disciplines, such as aerodynamics, structural analysis, mechanical design, and heat transfer etc. Considering the actual aero-thermal-structure coupled environment, the main challenge for the designers is to produce an optimum design that satisfies all the design criteria such as weight, life, efficiency and reliability.

Especially, problems of overweight and maximum localized stress have been always encountered for designers in the preliminary design phase. Therefore, there exist contradictions for the design parameters from different disciplines, and then multidisciplinary design optimization method could be a very valuable and efficient strategy to solve the problem.

In this paper, based on the platforms of ANSYS workbench software, the aero-thermal-structure coupled analysis of a high pressure turbine disk had been conducted. Then, the parameters of width and height of the disk bore were selected as the design variables, and multidisciplinary design optimization of turbine disk had been done. As a result, with the constraints on strength criteria, the objective function of disk weight had been decreased by 6 percents which achieved the expected goal and significantly reduced the design and research time.

Keywords: Turbine disk, Multidisciplinary Design Optimization

* Corresponding author. Tel.: +86-02133367163;
E-mail address: 34040209@163.com
1. Introduction

With the development of science and technology, the requirements of performance for aero engine are increasing. As we all known, the most efficient way to meet the requirements is to increase the turbine inlet temperature. The increase of turbine inlet temperature will inevitably raise the stress level of the turbine disc and thus affect the reliability and life of the engine. So the new high-temperature resistant materials as well as the complex cooling structure must be used to improve the turbine disc performance. The complex cooling structure can import a large amount of air to cool the blade and the disc and in this process the temperature difference between the rim and bore is reduced. Finally, it reduces the thermal stress. For cooling technology, on the one hand, the cooling effect must be reliable, on the other hand, for the purpose of minimizing the harmful impact on the engine efficiency, it is especially necessary that using the compressor air as little as possible on the premise of meeting the cooling requirement. This is a complex aerodynamic and heat transfer process.

What’s more, turbine disc works at high speed environment withstanding the tremendous centrifugal force and aerodynamic force caused by blades that involves complex aerodynamics, heat transfer, structural deformation, and others. We need to find a method to do accurate and comprehensive analysis of the disc’s work status. That is multidisciplinary design optimization.

The so-called multi-disciplinary design optimization (MDO) [1~2] is a new method proposed in recent years. The main idea of MDO is to integrate the various disciplines knowledge and use effective design optimization strategies and distributed computer network system to organize and manage the design process of complex systems. It is to get the overall system optimal solution by making full use of the synergies caused by the interaction of disciplines.

Since from the MDO concept was put forward, a lot of fluid-thermal-structure coupled study about the turbine disc and blade have been done [3~14], mainly for turbine blades about fluid-thermal or thermal-structure coupled. Among them, [12~14] are relatively perfect in coupled problems. Reference [12] described an overview of the loosely coupled model and a unified finite element method of solving fluid-thermal-structure problem. Reference [14] proposed two kinds method of the three dimensional model when do multi-disciplinary analysis, brought about the pass of data between the different disciplines meshed modal, and established a multidisciplinary method.

Based on the above research of the fluid-thermal coupled and thermal-structure coupled methods of blade, we developed the fluid-thermal-structure coupled optimization method of the turbine disc.

2. Objects

In the concept design phase, the turbine disk design is usually based on two-dimension FEM analysis which could be divided into two parts as is seen in Fig.1. Firstly, the design objective is the rim parts. Inputs are consisted of blade pull, root chord, number of blades, flow path radius, etc. To minimum the weight of attachment, the rim width, radius of live disk and basic shape parameters such as wedge angle, skew angle, the height of groove, etc. are selected as the design variables. Secondly, the live disk is another part to be optimized. The objective function is the weight of live disk, and the inputs are weights of blade and dead disk, rim radius, width of rim. Width of disk neck, radius of disk bore, width of disk bore and the height of disk, etc. are recommended as design variables [15].

But in the preliminary design phase, considering the complex environments including heat transfer, mechanical design and fluid analysis, three-dimension FEM analysis should be conducted to obtain the detailed geometry. By multidisciplinary design optimization process, the engine performance could be further improved and the weight be reduced.

In this paper, a high pressure turbine disk with 68 numbers of blade attachments was researched. The solid model for strength analysis is seen in Fig.2 (a), and fluid model for fluid-thermal analysis is seen in Fig.2 (b).
Disk concept design process

The attachment design

Attachment weight and life? No

The live disk design

Disk weight and life? No

Gate 1: review on the results

The end

Blade pull, root chord, number of blades, flowpath radius

weights of attachment, rim radius, width of rim

Fig. 1: Turbine disk concept design process

Fig. 2: (a) Turbine disk solid model, (b) Turbine disk fluid model
3. Multidisciplinary Design optimization

3.1. Design Process

Based on the ANSYS workbench software, the process of multidisciplinary design optimization in the preliminary design phase is seen in Fig. 3.

Parametric modeling of the turbine disk was performed by UG software. The feature parameters of disk and attachments could be selected as the design variables for optimization. After the disk geometry was imported into the Design Modeler (DM) module of ANSYS workbench, the feature parameters of disk could also be imported.

The fluid model was meshed by ICEM software in the Design simulation (DS) module. Then fluid-thermal coupled analysis of turbine disk was conducted by ANSYS CFX with certain boundary conditions. As a result, we got the temperature distribution of disks.

At the same time, in the Design simulation (DS) module, mesh, thermal and structure analysis of the solid model were performed with the interpolated disk temperature from fluid-thermal coupled analysis above.

Finally, the optimization design was developed in the Design Xplorer (DX) module by updating the design variables coming from UG software.

Fig. 3: Preliminary multidisciplinary design optimization process
3.2. Fluid-thermal coupled analysis

The separate iteration method, also known as loosely coupled method is the most common method in fluid-thermal coupled analysis of the turbine rotor. The whole calculation model will be divided into fluid domain and solid domain through this method. Firstly, with a certain specified solid wall temperature conditions, the fluid domain is analyzed to get the heat transfer coefficients of the solid domain. Secondly, the heat conduction equation in the solid domain is solved to get the temperature distribution of the solid domain. Lastly, taking this temperature distribution as boundary conditions, iterative process is carried out between fluid and solid domains until the result trends towards convergent.

The fluid-thermal coupled model includes fluid domain and solid domain, as is shown in Fig.4. Fluid domain includes disc cavity and internal cooling cavity of the root.

![Fluid domain and Solid domain](image)

Fig. 4: (a) Fluid domain, (b) Solid domain

The boundary conditions are inlet and outlet boundary, cyclic symmetry boundary and so on. The inlet and outlet boundary conditions are shown in Table1~2. The solid domain boundary conditions are shown in Table 3.

| Table 1. Inlet boundary conditions |
|-----------------------------------|
| **Name** | **Inlet1** | **Inlet2** |
| Pressure (MPa) | P | 0.88P |
| Temperature (K) | $1.08T_1$ | $T_1$ |

| Table 2. Outlet boundary conditions |
|-------------------------------------|
| **Name** | **Gas mass flow (kg/s)** | **Name** | **Gas mass flow (kg/s)** |
| outlet1 | m | Outlet4 | 1.73m |
| outlet2 | m | Outlet5 | 4.42m |
| outlet3 | 1.92m | Outlet6 | 4.42m |
Table 3 Solid model boundary conditions

| Name          | Blade root | Disk rim |
|---------------|------------|----------|
| Temperature (K) | $T_2$    | $T_2$    |

*For simplicity, some of the data use a non-dimensional representation.

We set the conservation equations to the standard upwind method, and use four bands Rung-Kutta method and k-$\varepsilon$ turbulence model. What’s more, in this study we have assumed that the fluid is inviscid and the left and right fluid walls are adiabatic, so in order to further simplify the calculation, the impact of speed is not taken into consideration.

Finally we got the heat transfer results of the turbine disk under steady-state flow. The speed streamlines and temperature distribution results are shown in Fig.5.

![Fig. 5: (a) Speed streamlines (Unit: m/s), (b) Temperature distribution (Unit: K)](image)

3.3. Thermal-structure coupled analysis

The static structure analysis is calculated based on the fluid-thermal coupled results. By interpolating the fluid-thermal coupled results as the boundary conditions of elastic-plastic stress analysis, we could get the stress distribution of the turbine disk.

The meshed cyclic symmetry model of turbine disk is shown in Fig. 6(a). Boundary conditions contained axial displacement constraints, cyclic symmetry boundary conditions, and the contact boundary between blade root and disk.

The temperature data was transferred through GGI interface of CFX. The steady-state thermal analysis results are plot in Fig.6 (b).
Through thermal-structure coupled calculation, the radial stress distribution of the turbine disk and blade is shown in Fig. 7. We can see that the maximum radial stress is at the web and the fillet of the third tooth region.

4. Results and discussion

The optimization design variables including width of disk bore and height of disk bore are listed in Table 4. And the optimization results are seen in Table 5.

From the results above, we can see that the total weight of the disks is decreased by 6% through the proposed fluid-thermal-structure coupled optimization design method. However the average hoop stress of disks is increased by 7%, but still meets the burst margin requirements.

Table 4 Design variables

| Variables | Name                | Lower limit | Upper limit |
|-----------|---------------------|-------------|-------------|
| DS_W1     | width of disk bore  | 1.000       | 1.334       |
| DS_H1     | height of disk bore | 0.429       | 0.715       |
Table 5 Optimization results

| Variables                      | Before optimization | After optimization | Difference |
|--------------------------------|---------------------|--------------------|------------|
| DS_W1                          | 1.190               | 1.084              | -8.91%     |
| DS_H1                          | 0.619               | 0.429              | -30.7%     |
| Weight (the objective function)| 1.000               | 0.942              | -5.87%     |
| Maximum hoop stress            | σ                   | 1.113σ             | +0.11%     |
| Average hoop stress            | 0.799σ              | 0.853σ             | +6.70%     |
| Maximum radius stress          | 0.758σ              | 0.715σ             | -5.73%     |
| Burst margin                   | 1.35                | 1.25               | -7.40%     |

*For simplicity, some of the data use a non-dimensional representation.

And the response surface of weight and maximum hoop stress of disk to design variables has been also plot in Fig.8.

![Response surface of disk weight (Unit: Kg)](image)

![Response surface of maximum hoop stress of disk (Unit: MPa)](image)

5. Conclusions

Through all the research, this paper proposed multidisciplinary coupled analysis method of a high pressure turbine disk model in the preliminary design phase. Based on the accomplishment of data transfer between different disciplines and different meshed model, we finished multidisciplinary design optimization of turbine disk. The optimization made the weight reduced by 6 percents which is of great significance. However, the locations of inlet and outlet affect the airflow and cooling effect of the disc and we will do more research and optimization on them.

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