Conceptual Multidisciplinary Design Optimization of Commercial Aero-engine System

Fushui Guo¹, Shiqi Zhao¹, Xiaodong Zhou²*, Jun Fan³ and Dong Mi⁴

¹ AECC Commercial Aircraft Engine Co., Ltd., Shanghai, China
² State Grid General Aviation Company Limited, Beijing, China
³ Army Aviation Institute, Beijing, China
⁴ AECC Hunan Aviation Powerplant Research Institute, Zhuzhou, China

*819331507@qq.com

Abstract. Commercial aero-engine design is a complicated task, which involves many disciplines, such as thermodynamics, aerodynamics, solid mechanics, heat transfer and materials science. Besides, for the sake of market requirements, designing a commercial aero-engine should not only consider the performance, fuel consumption, thrust and weight, but also pay special attention to noise, emissions and other environmental indices. In order to balance conflicts among various discipline indicators, and design an aero-engine with high comprehensive performance, we apply the multidisciplinary design optimization (MDO) technology to the conceptual design of an aero-engine system in this paper. Particularly, the system conceptual design of a high-bypass-ratio turbofan aero-engine is selected as a case study. A total of five disciplines, including thermal cycle, aerodynamics, structural mechanics, emission and noise, are considered. Meanwhile, six modules are integrated and analysed carefully. These modules include performance evaluation at the design point, performance evaluation at fifteen different off-design points, engine size assessment, engine weight assessment, engine emission assessment as well as engine noise assessment. On the basis of these modules, a MDO platform is set up. In addition, one optimization study with a single target of fuel burn is carried out by utilizing the adaptive simulated annealing (ASA) algorithm. Moreover, another optimization with multiple targets of fuel burn as well as nitrogen oxide emission is also studied by employing the non-dominated sorting genetic (NSGA-II) algorithm. The results shows that the MDO method for the commercial aero-engine can obtain better solutions for the system by fully taking into account the mutual effects among different disciplines.

1. Introduction

Green, environmental friendliness, low cost as well as high comprehensive performance are the future development trends of the advanced commercial aircraft engine. Compared with the traditional design method, the multidisciplinary design optimization (MDO) method has a great advantage in meeting demands of modern aircraft engines. First proposed by Sobieski [1], MDO has drawn much attention to many researchers and has been widely applied in the field of aero-engine.

In academia, there have been a great number of research achievements on the MDO of aero-engine components, such as: the fan MDO [2], the compressor MDO [3], and the turbine MDO [4]. Additionally, some researchers explored the MDO of aero-engine system. Considering the disciplines such as aerodynamics, structural mechanics and noise, Leborgne [5] studied the optimization for low-
noise open-rotor engine. The results show that the MDO method can not only satisfy all constraints of aerodynamics and structural mechanics, but also improve the comprehensive performance of aerodynamics and noise. Jonathan [6] carried out the research of design and optimization for contra-rotating open rotors. In the paper, he presented a novel multidisciplinary design methodology which involved CFD, FEM and acoustics as well. These studies show that the MDO method can not only improve the efficiency of design, but also design products with high comprehensive performance by fully considering the interactions among various disciplines [7].

In industry, aero-engine manufacturers are also actively developing their multidisciplinary design systems. In 1999, NASA [8] published the Numerical Propulsion Systems Simulation (NPSS), which integrates the multi-fidelity simulations for different components or disciplines of the aero-engine. NPSS is aimed at reducing the development cost of the aero-engine by utilizing high fidelity models in the early design stage. In 2003, Jones [9] introduced the preliminary multidisciplinary design system of Rolls-Royce named Genesis, which integrates the thermodynamic cycle analysis, flow path design, structural mechanics analysis, cost assessment, and so on. In 2011, Donus [10] introduced the MTU’s preliminary design system Modular Performance and Engine Design System (MOPEDS). MOPEDS involves many disciplines such as thermodynamics, aerodynamics, structural mechanics, weight, noise and cost. Furthermore, Brophy [11] described the Whitney & Pratt Canada’s preliminary multidisciplinary design optimization system PMDO. These multidisciplinary design systems can effectively improve product performance, increase productivity as well as reduce design cost by balancing conflicts among various indicators in the early design stage.

It can be seen that the MDO method has obvious advantages over the traditional design method. In order to balance conflicts among various discipline indicators, and design an aero-engine with high comprehensive performance, we will apply the MDO technology to the system conceptual design of a commercial aero-engine in this paper.

2. Physical models

2.1. Performance evaluation at the design point
Performance evaluation at the design point is the core content of the aero-engine system design. One of its purposes is to select aerodynamics performance parameters by taking into account the technical levels of engine components. Another main purpose is to select the appropriate cycle parameters by employing thermal cycle analysis. According to the previous design experience, we choose the cruise installation state as the design point in this paper. Besides, the software GasTurb11 is re-developed to achieve the background operation. As a result, the software can be utilized by the Isight optimization platform to automatically assess the performance at the design point. Particularly, reasonable iterations are set in the software. For example, in order to obtain the desired thrust $F$, the air mass flow $W_2$ is chosen as an iterative parameter.

2.2. Performance evaluation at off-design points
On the basis of the engine working envelope, fifteen typical operating states are selected as off-design points. Similarly, the software GasTurb11 is re-developed to correlate the component design points with the component maps. Besides, the maps are scaled by utilizing standard maps and standard design point setting. Therefore, the performance at each off-design point could be evaluated. As a result, some calculated parameters at the off-design points will be used as input parameters of the noise assessment module or the emission assessment module, while others will be used as part of the objectives or constraints.

2.3. Engine size assessment
In 1970s, NASA released the WATE-series methods for evaluating the aero-engine size and the aero-engine weight. On the basis of WATE-series methods, the NPSS evaluation method was developed subsequently. Referring to these methods, the self-developed software is selected to assess the engine
size in this paper. In detail, the preliminary geometry structure can be obtained with the help of Smith diagrams of the engine components. Particularly, we will take the compressor size estimation as an example to explain the method. First, the inlet and outlet thermal parameters of the components can be obtained through the performance evaluation at the design point. Then, the flow coefficient and work factor can be estimated with the help of Smith diagram of the components.

2.4. Engine weight assessment
Having obtained the main geometry structure according to the engine size assessment, we can easily estimate the weight of the main components, which include fan, booster compressor, high pressure compressor, combustion chamber, high pressure turbine, low pressure turbine, nozzles, shafts, supporting structure and accessories. Particularly, we will select a single stage compressor as an example to illustrate the process roughly. In details, the single stage compressor is mainly composed of four parts, namely the blade, disc, connecting piece and casing. Through reasonable simplification, we can calculate the volumes at first. Then, the weight can be estimated by combining the characteristics of the material. It should be noted that the material characteristics are default in the process. Accordingly, the whole engine weight can also be obtained.

2.5. Engine emission assessment
ICAO simplified a complete flight process into a LTO (Land and take off) cycle. That is to say, the complete flight process is divided into four off-design point states, namely LTO taking off state, LTO climbing state, LTO approaching state and LTO idling state. On the basis of the LTO cycle, various emission assessment methods have been proposed. These methods include P3T3 method, BFFM2 method, DLR method and ICAO method. In this paper, the BFFM2 method is chosen to evaluate the engine emission. In detail, the BFFM2 method utilizes the ICAO emission database to get the empirical correlation between the emission and the fuel flow.

2.6. Engine noise assessment
Generally speaking, for the high-bypass-ratio turbofan engine, there are four main noise sources, namely the fan noise, core noise, turbine noise and jet noise. Nowadays, various noise forecasting methods have been proposed to evaluate the four different noise sources by many researchers. For example, the H-W model and Rawls-Yeager model have been used to estimate the fan noise, the Mathews-Rekos model and ICAO model have been used to assess the core noise, the KV model and Matta-Sandusky-Doyle model have been used to evaluate the turbo noise, and the Stone model has been used to forecast the jet noise. In this paper, we employ the self-developed software to assess the major noise sources. And the whole aero-engine noise can therefore be estimated. Considering requirements of CCAR36 for noise, we should note that only noise in the overflying state, approaching state and boundary state is evaluated in this paper.

3. Optimization models
3.1. Single-objective optimization
3.1.1. Objective. The thermal cycle parameters of the aero-engine can affect not only the engine thrust and fuel consumption, but also the engine weight and nacelle size. Furthermore, these influences can cause changes of the aircraft’s weight as well as the aircraft's flight performance. Therefore, in order to obtain the optimal performance for the aero-engine, it is very necessary and important to conduct the aircraft/engine integrated design. So the fuel burn $FB$ can be calculated. The detailed procedure needs to discretize the entire mission into very small segments at first and then calculate $FB$ step-by-step. However, on one hand, it will take a long time to conduct the detailed procedure. On the other hand, it is difficult to ensure that every calculation step converges when the design variables vary in large ranges. Therefore, in this paper we introduce the weighted fuel consumption $sfc$, which can be
expressed as Eq. (1). In Eq. (1), \( sfc_{(i)} \) is a parameter which denotes the fuel consumption at each typical operating state, and \( w_i \) is a weighted coefficient which can determine the contribution of the fuel consumption at each typical operating state. In addition, by conducting the flight mission analysis, we can obtain the approximation functional relationship among \( \delta FB \), \( \delta sfc \) and \( \delta m_E \). The relationship can be represented as Eq. (2), where \( \delta FB \) denote the changing rate of \( FB \), \( \delta sfc \) denote the changing rate of \( sfc \), and \( \delta m_E \) denote the changing rate of \( m_E \). At last, \( \delta FB \) is chosen as the optimization objective in the case of single-objective optimization (SOO).

\[
\begin{align*}
\text{sfc} &= \sum w_i \times sfc_{(i)} \\
\delta FB &= f_e \left( \delta m_E, \delta sfc \right)
\end{align*}
\]

3.1.2. Constraints. Considering emission requirements, we choose \( NO_x \) as a constraint.
- Considering noise requirements, we choose \( dB_{(9)} \), \( dB_{(10)} \) and \( dB_{(11)} \) as constraints.
- Considering size requirements, we choose \( Dt \) as a constraint.
- Considering the technical levels of components, we choose \( \pi_{TH(0)} \) and \( \pi_{TL(0)} \) as constraints.
- Considering material characteristics, we choose \( T_{(I(1))} \), \( T_{(I(2))} \), \( T_{(I(4))} \), \( T_{(I(4))} \), \( T_{(I(4))} \), \( T_{(I(4))} \) and \( AN^2 \) as constraints.

In summary, a total of 16 constraints are selected in the case of SOO.

3.1.3. Design variables. In order to meet various indicators discussed above, the cycle parameters should be chosen carefully. According to the previous design experience, we choose five design variables in this paper. They are \( B \), \( \pi_F \), \( \pi_{CL} \), \( \pi_{CH} \) and \( T_{(4)(0)} \).

3.2. Multi-objective optimization

In order to meet demands of the green and environmental friendliness, we should pay more attention to the performance and emission. Therefore, \( \delta FB \) and \( \delta NO_x \) are selected as optimization objectives in the case of multi-objective optimization (MOO). Compared to the SOO problem, the design variables of the MOO problem remain unchanged, but \( NO_x \) is no longer treated as a constraint.

4. Optimization algorithms

With the help of the Isight software, a conceptual multidisciplinary design optimization platform for the system design of the commercial aero-engine is set up. The computing platform is an HP Z820 desktop workstation, which is configured with a 64GB memory, and a 20 Intel (R) Xeno (R) CPU E5-2680e clocked at 2.8GHz.

The Adaptive Simulated Annealing (ASA) is chosen to deal with the SOO problem. First proposed by Lester on the basis of traditional simulated annealing method and simulated quenching process, the ASA algorithm has become more and more popular in both science research and engineering tasks.

The Non-dominated Sorting Genetic Algorithm (NSGA-II) is chosen to deal with the MOO problem. The method was improved by Deb on the basis of the NSGA algorithm. It has the advantage of selecting excellent individuals by using the non-dominated sorting method.
5. Results and discussion

5.1. Single-objective optimization

The optimization converges after 2188 iterations, which takes 63 hours 36 minutes and 5 seconds in total. Figure 1 shows the convergence process of the objective in the case of SOO, where the red points represent infeasible solutions, the green ones represent feasible solutions, and the blue circle represents the optimal solution. From it we can see: 1) In the optimization, 566 feasible solutions are obtained. 2) The optimal solution is obtained at the 2066th iteration. 3) Particularly, the result from the vicinity of the 500th iteration is close to the optimal solution. It shows that the ASA algorithm can converge quickly to the optimal solution.

Figure 1. Convergence process of the objective function in the case of single-objective optimization.

Comparing the optimal scheme with the initial scheme, we can calculate the changing rate of the optimal solution. The detailed information is showed in Table 1, from which we can see: the fuel burn $FB$ is reduced by 2.85%; the weighted fuel consumption $sfc$ is reduced by 1.93%; the total weight of the aero-engine $m_E$ is reduced by 3.23%; the emission of nitrogen oxides $NO_x$ is reduced by 7.21%; the noise index $dB_{(9)}$ and $dB_{(10)}$ are reduced by 0.19% and 0.26% respectively. Meanwhile, the bypass ratio $B$ is increased by 16.46%; the fan pressure ratio $\pi_F$ is reduced by 0.66%; the pressure ratio of the low pressure compressor $\pi_{CL}$ is reduced by 2.42%; the pressure ratio of the high pressure compressor $\pi_{CH}$ is reduced by 7.40%; the total temperature at the combustor exit $T_{4(0)}$ is reduced by 1.04%.

Table 1. Optimal solution in the case of single-objective optimization.

|       | $FB$   | $sfc$  | $m_E$  | $NO_x$ | $dB_{(9)}$ | $dB_{(10)}$ | $dB_{(11)}$ | $Dt$  |
|-------|--------|--------|--------|--------|------------|------------|------------|-------|
| **changing rate** | -2.85% | -1.93% | -3.23% | -7.21% | -0.19%     | -0.26%     | 0.12%      | 2.35% |
| $\pi_{TH(0)}$ |        |        |        |        |            |            |            |       |
| $\pi_{TL(0)}$ |        |        |        |        |            |            |            |       |
| $T_{3(1)}$    |        |        |        |        |            |            |            |       |
| $T_{3(2)}$    |        |        |        |        |            |            |            |       |
| $T_{3(4)}$    |        |        |        |        |            |            |            |       |
| $T_{4(0)}$    |        |        |        |        |            |            |            |       |
| $T_{4(1)}$    |        |        |        |        |            |            |            |       |
| $T_{4(2)}$    |        |        |        |        |            |            |            |       |
| $T_{4(3)}$    |        |        |        |        |            |            |            |       |

|       | $T_{4(4)}$ | $T_{4(5)}$ | $AN^2$ | $B$    | $\pi_F$  | $\pi_{CL}$ | $\pi_{CH}$ | $T_{4(0)}$ |
|-------|------------|------------|--------|--------|----------|------------|------------|------------|
| **changing rate** | -15.08%   | 13.26%     | -3.22% | -3.22% | -2.85%   | -1.50%     | -1.47%     | -1.48%     |
| $T_{4(4)}$ |            |            |        |        |          |            |            |            |
| $T_{4(5)}$ |            |            |        |        |          |            |            |            |
| $AN^2$  |            |            |        |        |          |            |            |            |
| $B$    |            |            |        |        |          |            |            |            |
| $\pi_F$ |            |            |        |        |          |            |            |            |
| $\pi_{CL}$ |            |            |        |        |          |            |            |            |
| $\pi_{CH}$ |            |            |        |        |          |            |            |            |
| $T_{4(0)}$ |            |            |        |        |          |            |            |            |

|       | $T_{4(4)}$ | $T_{4(5)}$ | $AN^2$ | $B$    | $\pi_F$  | $\pi_{CL}$ | $\pi_{CH}$ | $T_{4(0)}$ |
|-------|------------|------------|--------|--------|----------|------------|------------|------------|
| **changing rate** | -1.01%    | 4.82%      | -11.82%| 16.46% | -0.66%   | -2.42%     | -7.40%     | -1.04%     |
| $T_{4(4)}$ |            |            |        |        |          |            |            |            |
| $T_{4(5)}$ |            |            |        |        |          |            |            |            |
| $AN^2$  |            |            |        |        |          |            |            |            |
| $B$    |            |            |        |        |          |            |            |            |
| $\pi_F$ |            |            |        |        |          |            |            |            |
| $\pi_{CL}$ |            |            |        |        |          |            |            |            |
| $\pi_{CH}$ |            |            |        |        |          |            |            |            |
| $T_{4(0)}$ |            |            |        |        |          |            |            |            |
As expected, the results indicate that the MDO method of aero-engine system based on ASA algorithm can obtain a better solution of the system with all the constraints being satisfied. It just shows that the proposed method has an obvious advantage in considering the mutual effects among all the five disciplines discussed in this paper.

5.2. Multi-objective optimization
The optimization converges after 2241 iterations, which takes 62 hours 3 minutes and 26 seconds in total. Specifically, 941 feasible solutions and 2 Pareto solutions are obtained in the process of optimization. Figure 2(a) and figure 2(b) show the convergence process of the objectives, namely $FB$ and $NO_x$, in the case of MOO. Figure 3(a) shows the Pareto front in the case of MOO. Besides, the local information near the optimal solutions is amplified in figure 3(b). From these figures, we can see:
1) In the optimization, two Pareto solutions are obtained respectively at the 2239th iteration and the 2241th iteration. 2) Particularly, the objectives reduce significantly in the vicinity of 1300th iteration, which shows that the NSGA-II algorithm has the ability of avoiding trapping in the local optimum.

The solution with the minimal $FB$ is selected as the optimization scheme 1. And the solution with the minimal $NO_x$ is selected as the optimization scheme 2. The detailed information is listed in Table 2, from which we can see: 1) When comparing optimization scheme 1 with the initial scheme, the fuel burn $FB$ is reduced by 2.82%, meanwhile the emission of nitrogen oxides $NO_x$ is reduced by 7.06%. 2) When comparing the optimization scheme 2 with the initial scheme, the fuel burn $FB$ is reduced by 2.80%, meanwhile the emission of nitrogen oxides $NO_x$ is reduced by 7.08%. 3) It's obvious that the two optimization schemes are similar. In detail, the difference for the fuel burn $FB$ is only 0.02%, and the difference for the emission of nitrogen oxides $NO_x$ is still 0.02%.

|   | $FB$  | $NO_x$ | $sfc$  | $m_E$  | $B$   | $\pi_F$ | $\pi_{CL}$ | $\pi_{CH}$ | $T_{4(0)}$ |
|---|-------|--------|--------|--------|-------|---------|------------|------------|-----------|
| 1 | -2.82 | -7.06  | -1.98  | -2.20  | 18.34 | -0.57   | 10.16      | -0.75      | -1.02     |
| 2 | -2.80 | -7.08  | -1.95  | -2.33  | 18.42 | -0.37   | 10.07      | -0.70      | -1.05     |

Table 2. Pareto solutions in the case of multi-objective optimization.

As expected, the results discussed above indicate that the MDO method of aero-engine system based on NSGA-II algorithm has the advantage of "Optimize at first, and then make decisions". That
is to say, it doesn't need to consider the preference of the designer at first. On the contrary, it can obtain a set of Pareto solutions for the designer to make final decision.

5.3. Comparison and discussion
We find some differences in results between the SOO case and MOO case. Therefore, it's necessary to discuss the advantages and disadvantages of the two cases.

From Figure 1 and Figure 2, we can see the result at the 500th iteration is close to the optimal solution in the SOO case, yet in the MOO case the results at the 1200th iteration is still far away from the Pareto solutions. Obviously, the SOO case performs better than the MOO case in efficiency. But what leads to such a result? We think the reason is that the MOO case traps in the local optimum before the 1200th iteration.

When comparing the optimization results, we can find that the optimal scheme in the SOO case is better than both the Pareto solutions in the MOO case. Similarly, what leads to such a result? Figure 3(a) shows that there is a positive correlation between $FB$ and $NO_x$. That is to say, there is no obvious conflict between the two indicators. Therefore, in the SOO case, $NO_x$ decreases with the reduction of $FB$.

![Figure 3. Pareto front in the case of multi-objective optimization.](image)

In summary, for the problem in this paper, the SOO case performs better than the MOO case both in results and efficiency.

6. Conclusion
In this paper, a high-bypass-ratio turbofan aero-engine was selected as a case study. A total of five disciplines were considered. Six modules were integrated and analysed carefully. Besides, a MDO platform for the system conceptual design of the commercial aero-engine was set up. Through the research, we can get the following conclusions.

- The conceptual MDO method for the commercial aero-engine system is an advanced design method. It has a great advantage in considering the mutual effects among all the five disciplines discussed in this paper. It can obtain better solutions of the system.
- The MDO method of aero-engine system based on ASA algorithm can converge quickly to the optimal solution of the system with all the constraints being satisfied. The optimal fuel burn $FB$ is reduced by 2.85%; the optimal emission of nitrogen oxides $NO_x$ is reduced by 7.21%.
- For the problem in this paper, the SOO case performs better than the MOO case in both results and efficiency.
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