Chinese Journal of Aeronautics, (2016), 29(6): 1541–1552

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Aerodynamic optimization of rotor airfoil based on multi-layer hierarchical constraint method

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Received 21 December 2015; revised 12 May 2016; accepted 27 May 2016
Available online 21 October 2016

KEYWORDS

Multi-layer hierarchical constraint method;
Multi-objective optimization;
NSGA II;
Pareto front;
Principal component analysis;
Rotor airfoil

Abstract Rotor airfoil design is investigated in this paper. There are many difficulties for this high-dimensional multi-objective problem when traditional multi-objective optimization methods are used. Therefore, a multi-layer hierarchical constraint method is proposed by coupling principal component analysis (PCA) dimensionality reduction and ε-constraint method to translate the original high-dimensional problem into a bi-objective problem. This paper selects the main design objectives by conducting PCA to the preliminary solution of original problem with consideration of the priority of design objectives. According to the ε-constraint method, the design model is established by treating the two top-ranking design goals as objective and others as variable constraints. A series of bi-objective Pareto curves will be obtained by changing the variable constraints, and the favorable solution can be obtained by analyzing Pareto curve spectrum. This method is applied to the rotor airfoil design and makes great improvement in aerodynamic performance. It is shown that the method is convenient and efficient, beyond which, it facilitates decision-making of the high-dimensional multi-objective engineering problem.

1. Introduction

It is, as is universally accepted, difficult to conduct optimization design for rotor airfoil to improve the performance of helicopter as it involves many conflictive objectives and constraints. During the whole flight process of helicopter, blades of rotor have to work in an extremely complex aerodynamic condition associated with a large spectrum of flow region. Especially for forward flight, the Mach number around the tip of the advancing blade reaches up to transonic regime, leading up to a shock wave/boundary layer interaction. At the same time, to maintain helicopter roll stability, the local lift of retreating side needs to be high enough to balance the advancing blade in high dynamic pressure, so the retreating blade has to work at low speed and high angle of attack, which may cause local flow separation in the outer region. All the fight conditions request that the airfoils have a high maximum

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.09.005
1000-9361

lift coefficient at the low and moderate subsonic Mach state with a small zero-lift drag coefficient and high drag divergence property at transonic state at the same time. Beyond that, a small pitching moment is essential to reduce the torque and control loads. In addition, the rotor airfoil is also required to have a high lift-to-drag ratio in the hover state. So the rotor airfoil design is a multi-objective multi-constraint problem.[1,2]

Compared to the airfoil of fixed-wing aircraft, research of rotor airfoil design evolves slowly, mainly because of the complex design requirements. However, as the main element of the rotor blade, the performance of helicopter is determined by the airfoils to a great extent. Therefore, with the further development of aeronautic technology, efficient design of high-performance rotor airfoil is possible and particularly important to improve the overall performance of the helicopter.[3] In the early years, symmetrical airfoil was often used as rotor airfoil due to various reasons. Until the 1970s, with the increase of helicopter flight speed, airfoil had become the key obstacle to improving performance of the helicopter. After twenty years' research conducted by NASA, ONEAR, Boeing and other research institutions, a series of advanced airfoils were developed, such as OA series, VR series, and TsAGI series,[4–6] and the performance of helicopter was substantially improved. Recently, Vu et al.[7] made use of genetic algorithm and the two-dimensional viscous panel method, XFOIL, to optimize rotor blade airfoils within a single-objective/multipoint formulation, considering forward flight and hover conditions. Massaro and Benini[8] proposed a multi-objective approach for rotor airfoil optimization under a fixed condition using a framework of integrated GA and gradient-based algorithms. At home, recently Yang et al.[9] did some work for rotor airfoil with average method. Wang et al.[10] did some optimization work for helicopter airfoil considering the dynamic stall characteristic. However, the above work considered only part of requirements, so only the specific performance was improved.

If all the design requirements are considered, a high-dimensional multi-objective problem will be resulted in, which has to be solved by relevant algorithm. In recent years, with the rise and development of intelligent optimization techniques, research on solving multi-objective optimization problem has become a hot spot. Evolutionary algorithms treat the entire solution set as the evolution group, and search Pareto optimal solution set in a parallel manner. It becomes the best way to solve complex engineering problems with multi-objective constraints. Currently, however, the problem with more than four objectives is intractable enough for evolutionary optimization.[11–14] Thus, two or three optimization objectives are often involved in general engineering optimization. With the increase of the objective number, dimension of Pareto optimal front surface increases and even worse, and the number of Pareto optimal frontier points grow exponentially, which will greatly increase the algorithm's time and space complexity. At the same time, the number of non-dominated solutions leaps severely. For a fixed scale external group, outstanding individuals in the evolutionary process may not be preserved so that the whole search process will slow down. Traditional optimization methods, such as NSGA II,[15,16] are ill in handling this kind of problems. In addition, with the increase of the objective number, the visualization of optimization results becomes difficult, which hinders the selection of optimal results for further decision-making. Although there are several methods in the auxiliary display area, it is at the expense of large-scale calculations. To solve this problem, extensive research has been carried out, which is mainly divided into two aspects: (A) improving the optimization algorithm to make it more suitable for high-dimensional optimization problem by defining loose Pareto dominant mechanism, increasing selection pressure of individuals, and thus speeding up the convergence of the algorithm. However, it is still a problem whether these improvements are suitable for engineering. Moreover, even if we can get the optimal solution set, the calculation is too expensive and it is difficult to show optimized results for further decision-making. (B) Reducing the high-dimensional multi-objective optimization problem to a low-dimensional optimization problem by introducing dimension reduction method in mathematical analysis. But such method is still at the theoretical level and can be rarely used in complex engineering applications. Therefore, it is of great theoretical and practical significance to develop a method for these problems.

Therefore, in this paper, a multi-layer hierarchical constraint (MHC) method is proposed referring to e-constraint method[17] to translate the complex optimization problem into a bi-objective optimization problem. The paper is organized as follows: Section 2 gives the rotor airfoil design requirements and sets up the many-objective optimization model. The principal component analysis—non-dominated sorting genetic algorithm II (PCA-NSGA II) method and multi-layer hierarchical constraint method are given in Section 3. In Section 4, different methods are compared for rotor airfoil design. A discussion of the main findings concludes the paper in Section 5.

2. Design criteria and model for rotor airfoils

The airfoils experience drastically different conditions within a single blade revolution. Especially for forward flight, the rotor airfoil works inside a broad range of Mach numbers and angles of attack, so the advanced rotor airfoil design often meets conflicting design requirements. Specifically, the advanced rotor airfoil design should satisfy the following requirements:

(1) A high maximum lift coefficient $C_{L\max}$ under condition of $Ma = 0.3$–0.5 to postpone the separation of retreating blade stall and reduce blade vibration at high-speed.
(2) High drag divergence Mach number ($C_L = 0$) and low transonic drag coefficient to reduce noise and the power requirement for forward flight.
(3) High lift-to-drag ratio characteristics ($Ma = 0.5$–0.6, $C_L = 0.6$) to ensure the rotor hover efficiency.
(4) Very low zero-lift pitching moment coefficient C_{m0} to reduce the blade torsion and manipulate load of the control system.

Considering all the above design requirements, the following design objectives and constraints, as shown in Table 1, can be obtained.

Referring to Table 1, the following optimization model can be constructed: