ARTICLE IN PRESS

Chinese Journal of Aeronautics, (2018), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Pressure distribution guided supercritical wing optimization

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Received 4 April 2018; revised 13 April 2018; accepted 15 May 2018

KEYWORDS

Aerodynamic optimization;
Man-in-loop;
Pressure distribution;
RBF-assisted;
Supercritical wing

Abstract Pressure distribution is important information for engineers during an aerodynamic design process. Pressure Distribution Oriented (PDO) optimization design has been proposed to introduce pressure distribution manipulation into traditional performance dominated optimization. In previous PDO approaches, constraints or manual manipulation have been used to obtain a desirable pressure distribution. In the present paper, a new Pressure Distribution Guided (PDG) method is developed to enable better pressure distribution manipulation while maintaining optimization efficiency. Based on the RBF-Assisted Differential Evolution (RADE) algorithm, a surrogate model is built for target pressure distribution features. By introducing individuals suggested by sub-optimization on the surrogate model into the population, the direction of optimal searching can be guided. Pressure distribution expectation and aerodynamic performance improvement can be achieved at the same time. The improvements of the PDG method are illustrated by comparing its design results and efficiency on airfoil optimization test cases with those obtained using other methods. Then the PDG method is applied on a dual-aisle airplane's inner-board wing design. A total drag reduction of 8 drag counts is achieved.

1. Introduction

Optimization design is more and more widely used to gain practical industrial designs in recent years. Multiple types of optimization algorithms have been well developed for more efficient and capable industrial optimal searching. However, although there have been many efforts using optimization algorithms to improve aerodynamic performances, practical design via optimization is still limited, and "cut-&-try" is still heavily relied on in the aircraft industry.[1] On one hand, even though multi-objective and multi-constraint optimization has become popular,[2,3] the complexity of industrial considerations makes it difficult to define all engineering-needed objectives and constraints for optimization algorithms.[4,5] On the other hand, engineers find their experiences, considerations, and judgments difficult to be introduced into an automatic optimization design process.[1,4,6–8] Therefore, in order to gain an engineering-acceptable design, optimization design not only needs a robust and flexible algorithm to endure a large amount of objectives and constraints, but also needs ways to transfer

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.06.021
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Please cite this article in press as: LI R et al. Pressure distribution guided supercritical wing optimization, *Chin J Aeronaut* (2018), https://doi.org/10.1016/j.cja.2018.06.021

those in-brain requirements into what the optimization algorithm can accept or process.

Experienced supercritical wing designers usually do not seek a wing with the highest lift/drag ratio, but a design that best compromises the performances of different disciplines and different flight conditions. What's more, they emphasize much on design robustness, such as the drag divergence Mach number, the buffet onset lift coefficient, etc. Since both the performance and robustness are essentially the outcomes of flow structures as well as their evolutions, the flow physics is relatively clear. Engineers tend to judge a design through flow patterns and details. Currently, pressure distribution is the most cared flow structure in supercritical wing design. Many rules or criteria on pressure distribution have been proposed. For instance, the shock should be properly located to get a good robustness, and the aft loading of an airfoil should not be too large or else the nose-down pitching moment could be unacceptable.[9–11]

By realizing these explicit rules of hint experiences on pressure distribution, a designer could improve a wing's design point performances while achieving preferable off-design and multi-disciplinary properties. This is basically what they do in "cut-&-try". From the 1980s, with the development of inverse design methods[12–14] researchers tried to gain a design by realizing a desired pressure distribution. However, due to the difficulties of "designing" a physically-existing pressure distribution, even for a simple geometry at a specific flow condition,[11,15] the application of these methods in the industry is still limited.

Zhang et al.[16] studied the drag, moment, and especially robustness of three categories of typical pressure distributions for supercritical airfoils, i.e., shock-free, double shock, and weak shock. The weak shock pressure distribution was evaluated as the best. Furthermore, other suggestions on pressure distribution have been proposed, such as that the shock location should range from 45% to 55% chord length for a single-aisle civil aircraft, the aft-loading should compromise the lift generation and a mild pitching moment, etc. To realize these suggestions, methods were developed to induce the pressure distribution to approach a desired pattern during optimization design. Some of them have been proven effective in industrial design. Optimal searching is no longer driven only by performances, but also by pressure distributions. Such methods are generalized in the present paper as Pressure Distribution Oriented (PDO) optimizations.

The PDO method has also been applied to a dual-aisle airplane wing design.[17] The cruise performance and robustness were improved while the proposed weak shock pressure distribution was also achieved. The shock location was pushed slightly downstream that of a single-aisle civil aircraft to fit a higher Reynolds number and different cruise lift coefficients. Both the single- and dual-aisle design studies have shown that the location of shock wave is a critical factor for a supercritical wing's balance of performance and robustness.

Since the PDO method is characterized by the ability of manipulating pressure distributions, it can be consequently used to study the performance of a specified type of pressure distribution. By using the PDO method, Zhang et al.[18] achieved supercritical natural laminar airfoils with different pressure distributions characterized by assigned favorable pressure gradients and shock locations. Their gains on laminar friction reduction and penalties on the wave drag and robustness were then systematically compared.

There are two types of PDO optimization developed in previous studies according to their methods of manipulating pressure distributions. The first one can be called Pressure Distribution Constrained (PDC) method.[16–18] Constraints are set to rule out or punish designs with an unsatisfying pressure distributions shape. It essentially posts restrictions on the optimal search direction. The optimization efficiency and global optimal searching capability are inevitably deteriorated.

The other method is a manual or "man-in-loop"[1,16] one. Engineers can guide an optimization's pressure distribution trend by manipulating the population. They need to introduce external individuals, which have the expected pressure distribution characteristics, into the population, or they need to eliminate unsatisfactory individuals from the population. This method demands a large amount of human labors and experiences.

In this paper, a new approach of using the pressure distribution expectation to guide optimization is developed. Instead of manual population control, the so-called Pressure Distribution Guided (PDG) method uses a surrogate model to search potential individuals which best satisfy the expectation on pressure distribution and also have excellent performances. These individuals are introduced into the population of an evolutionary optimization algorithm. In this way, the optimization process is automatically guided to approach the expected pressure distribution feature, while the diversity of the population during the optimization is well preserved. To more rationally define the "expectation" on the pressure distribution, several physical or empirical relations are also studied.

Unlike the PDC method, the pressure distribution is pursued by "guidance from good individuals" instead of "punishing bad individuals".

As a new branch of PDO optimization, in the present paper, the idea of the PDG method is firstly introduced. It is then tested and compared with previous methods by airfoil cases. Proven by results that it has better optimal searching efficiency and pressure distribution manipulation capabilities, the PDG method is applied to the supercritical wing design of a dual-aisle civil airplane.

2. Optimization and modeling methods

2.1. RBF assisted differential evolution algorithm

An evolutionary optimization algorithm can use the assistance of surrogate models to improve efficiency.[19] In the present study, an RBF (radial basis function) Assisted Differential Evolution (RADE) algorithm is used as the primary optimization algorithm.[20] The basic flow chart of the RADE algorithm is outlined in Fig. 1(a), in which k is the index of the current generation and P is short for population. The dash box contains the main optimization process of Differential Evolution (DE) optimization, and the upper part outside the box shows the RBF surrogate model's behavior. By utilizing computed individuals' information, the RBF surrogate model can obtain approximation of CFD results. Then an optimal search is conducted on the RBF response surface to find individuals that are most likely to produce excellent objectives. Those

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