Aerospace Science and Technology 43 (2015) 152–164

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Supercritical natural laminar flow airfoil optimization for regional aircraft wing design [☆]

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ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form 26 February 2015
Accepted 27 February 2015
Available online 4 March 2015

Keywords:
Airfoil
Optimization
Natural laminar flow
Pressure gradient constraint
Favorable pressure gradient

ABSTRACT

An optimization design method of supercritical natural laminar flow airfoil based on Genetic Algorithm and Computational Fluid Dynamics is tested in this paper. Class Shape Transformation method is adopted as geometry parameterization method. Constraints on pressure distribution are applied to gain appropriate flow field in addition to the L/D performance. A fixed transition computation method is used in the optimization process to save computation time while giving the reasonable friction drag estimation and predicting the influence of the laminar boundary layer on airfoil performances. Specified favorable pressure gradient constraints are used to guarantee the expected laminar length. Objective of optimization is set to weaken the shock wave and minimize the pressure drag. Such a simplified NLF optimization process is verified by natural transition computation. The optimal setting of the favorable pressure gradient constraint, which is important for the trade-off between drag reduction and laminar stability, is then studied via numerical investigation. Results show that the airfoil optimized by constraining a favorable pressure gradient larger than 0.2 is good for both cruise efficiency and robustness. A natural laminar wing is then designed based on the optimized airfoil. Numerical verifications show that the wing has good natural laminar performance and low speed behavior.

1. Introduction

Natural Laminar Flow (NLF) airfoil has already been studied for several decades [15]. However, it still draws high attention in recent years. As the friction drag is about half of the total drag for modern civil aircrafts [10], laminar technology has great potential to increase lift to drag ratio. Although a lot of flight tests had successfully validated the efficiency of NLF airfoil on modern large civil aircrafts [16,6], the technology is only realized on wings of several light business aircrafts in the commercial market until now, such as the Honda Jet [11,13] and the Aerion Supersonic Business Jet [14,31]. Parameter analysis results of Lammering et al. [19] showed that, NLF design of a Boeing 777-size airplane could not show improvements on airplane direct operating costs than conventional turbulent design unless the drag reduction is more than 40 counts. In order to preserve laminar region, a lower leading edge sweep angle is adopted in the NLF wing [19]. Consequently, the cruise Mach number is quite lower than turbulent wing. Increasing cruise Mach number is as important as reducing skin friction for NLF wing design. Benefit and penalty of the NLF technology need to be clearly quantified.

Airfoil is a fundamental element of a wing. Many investigators have focused on the supercritical NLF airfoil design because of its importance for the high-subsonic NLF wing. Biber and Tilmann [4] developed a supercritical NLF design method based on the panel and Euler codes coupled with boundary layer equation, and attempted to increase the drag bucket of the NLF airfoil in order to extend the operational speed range. Eggleston et al. [9] showed that the peak Mach number, pressure gradient, and aft loading were critical factors of a favorable pressure distribution of an NLF airfoil. Cella et al. [5] successfully used the rule of cosine to design a high-subsonic NLF wing with a multi-objective optimization method. They separately designed the root/kink/tip airfoils and got

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[☆] Supported by National Key Basic Research Program of China (2014CB744801) and National Natural Science Foundation of China (11102098 and 11372160).

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http://dx.doi.org/10.1016/j.ast.2015.02.024
1270-9638/

Nomenclature

γ	Turbulence intermittency factor	$C_{d,p}$	Pressure drag coefficient
Re_θ	Reynolds number based on boundary layer momentum thickness	$C_{d,f}$	Friction drag coefficient
Ma	Mach number	C_m	Pitching moment
C_p	Pressure coefficient	L/D	Lift to drag ratio
C_f	Friction coefficient	$\mathrm{d}C_p/\mathrm{d}X$	Pressure coefficient gradient of airfoil
C_l	Lift coefficient	t/c	Airfoil relative thickness
C_d	Drag coefficient	c	Chord length
		Q_{FPG}	quantity of favorable pressure gradient, $-\mathrm{d}C_p/\mathrm{d}X$

an NLF wing with good laminar performance. Khalid and Jones [17] showed the supercritical NLF airfoils with different thicknesses designed at the National Aeronautical Establishment, and the experiment validated good performances of the airfoils at Reynolds number up to 12.5 million. Streit et al. [30] provided a new method of converting pressure distribution of two-dimensional NLF airfoil to three-dimensional wing by considering the sweep and tapered effects. The pressure distribution of the Honda jet [12] provided some new concepts of supercritical NLF airfoil design, on which the tailing edge bubble of the upper surface was adopted to suppress low speed flow separation, and the leading-edge shape was carefully designed to cause transition at high angles of attack (AoA) to obtain higher maximum lift coefficient. Shockwave/boundary layer interaction is a major cause of transonic drag rising. Aircraft designers would have an opportunity to raise cruise Mach number if they could decrease shock wave drag. That is a main objective of supercritical airfoil design. Apparently, another objective of supercritical NLF airfoil design is to decrease the friction drag. In realistic high-subsonic design practice, aerodynamic designer usually has a target (or an expectation) of laminar length for a certain condition based on experience or literature survey. Consequently, the potential of friction drag reduction is approximately confirmed. The design problem becomes how to achieve laminar length and how to reduce shockwave drag. Laminar flow length could be achieved through maintaining Favorable Pressure Gradient (FPG, or negative pressure gradient) [8]. However, the FPG should not be so great as to avoid excessive shock strength [8]. Nevertheless, the quantitative influence of FPG on drag of supercritical NLF airfoil is not so clear. Trade-off between wave drag and friction drag is a problem of NLF airfoil design, which is closely related to the FPG.

With the help of modern optimization methods, the application of NLF technology could be pushed forward. Genetic algorithm [35,2] and adjoint method [21,22] are two kinds of widely used optimization methods on airfoil design. Both methods have their inherent problems. The latter is lack of global optimization ability and difficult to treat realistic design constraints. The former has the probability to achieve global optimization solution, but requires lots of computation costs. Computation cost of CFD must be carefully controlled in genetic algorithm optimization. "Man-in-loop" design process is a practical compromise for engineering applications, for example, introducing some pressure distribution constraints in a design problem to guide optimization direction [34,33] and artificially adjusting the constraints and objectives during design iteration.

In this paper, supercritical NLF airfoil is optimized for the high-subsonic NLF wing of a regional jet. A Reynolds Averaged Navier–Stokes CFD solver is used as aerodynamic analysis tool. An in-house developed optimization platform [27] based on the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) [7] is adopted as background scheduling software. Class shape transformation (CST) method is employed as airfoil parameterization method. Optimization process is controlled by a series of realistic constraints. Supercritical NLF airfoil is obtained through optimization based on RAE2822 supercritical airfoil. Effect of FPG on laminar characteristics is investigated by six airfoils which are optimized by different pressure distribution constraints. A good compromise between pressure drag and friction drag is achieved when the FPG on the upper surface before 50% chord is larger than 0.2. A high-subsonic NLF wing is got by assembling and simply modifying the optimized airfoil. Numerical results demonstrate that the wing has both large laminar region and good robustness.

2. Numerical method and validation

2.1. Turbulence modeling

Aerodynamic analysis in this paper is based on a Reynolds Averaged Navier–Stokes CFD code. It is used to compute fixed transition flow field in the optimization, and to calculate natural transition flow field after optimization.

In NLF wing design, the accuracy of transition prediction is an important factor of design quality. Based on Shear Stress Transport (SST) model [23], a transition model had been developed by Menter et al. [24,25] through adding an intermittency factor (γ) equation and a momentum thickness based Reynolds number (Re_θ) equation to the turbulence models, called as SST γ–Re_θ model.

Because of the strong source terms in the SST γ–Re_θ model, the computation time of the SST γ–Re_θ model is much longer than the SST model, as the Courant–Friedrichs–Lewy number must be smaller. However, the computation time is a critical factor of genetic algorithm optimization. An alternative method is used in the present optimization process to reduce computation cost. The pressure distribution of airfoil is predicted by the SST turbulence model with fixed transition when optimizing the airfoil shape and the accurate transition location is validated by the SST γ–Re_θ model after optimization. The fixed transition location is located based on the design expectation of laminar length. The fixed transition computation could consider the influence of the laminar boundary layer and accurately predict the pressure drag. The laminar length is achieved through maintaining the FPG. In the next sub-section, the code is validated by two cases with experimental data. The pressure distributions of the fixed transition and natural transition computations are also compared.

2.2. Validation

In this paper, we mainly focus on transition prediction capability of the SST γ–Re_θ transition model for supercritical NLF airfoil. The transition prediction accuracy is validated by two test cases. The first is a low speed NLF airfoil, NLF 0416. It is used to test grid convergence, as well as fixed transition computation to ensure it as a cheaper substitution in the optimization process. The second case NLR 7301 is used to validate the transition prediction accuracy of transonic flow.