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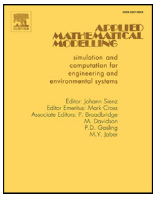

Natural laminar flow shape optimization in transonic regime with competitive Nash game strategy[☆]

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ABSTRACT

The Natural Laminar Flow (NLF) airfoil/wing design optimization is an efficient method which can reduce significantly turbulence skin friction by delaying transition location at high Reynolds numbers. However, the reduction of the friction drag is competitively balanced with the increase of shock wave induced drag in transonic regime. In this paper, a distributed Nash Evolutionary Algorithms (EAs) is presented and extended to multi-level parallel computing, namely multi-level parallel Nash EAs. The proposed improved methodology is used to solve NLF airfoil shape design optimization problem. It turns out that the optimization method developed in this paper can easily capture a Nash Equilibrium (NE) between transition delaying and wave drag increasing. Results of numerical experiments demonstrate that both wave drag and friction drag performances of a NE are greatly improved. Moreover, performance of the NE is equivalent to that of cooperative Pareto-optimum solutions, but it is more efficient in terms of CPU time. The successful application validates efficiency of algorithms in solving complex aerodynamic optimization problem.

1. Introduction

Aerodynamic drag is historically and conveniently separated into pressure or form drag (including interference and roughness drag), drag due to lift, shock or compressibility drag and viscous or skin friction drag. In the context of a civil or commercial transport aircraft, depending on the size, viscous or skin friction drag accounts for about $40-50\%$ of the total drag under cruise conditions; the payoff is generally high even with a small level of drag reduction [1]. There has been continuous and focused activity around the global concerning development of new techniques for skin friction drag reduction [2–4] and attempts have progressed broadly in two directions: methods for delaying laminar-turbulent boundary layer transition and methods for altering or modifying the turbulent structure of a turbulent boundary layer.

The earliest research in aeronautical viscous drag reduction addressed the issues of transition delay, initially via favorable pressure gradients on the essentially unswept wings of the day. Later, in the 1950s and 1960s, suction was utilized in research efforts to address the cross-flow instability problem endemic on swept wings. This early research on transition delay was termed Laminar Flow Control (LFC), with Natural Laminar Flow (NLF) defined by pressure gradient controlled/delayed transition and forced or active laminar flow obtained via suction. This technology offered large gains in aircraft performance

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and was actively pursued, at various times, in many countries, e.g. the United States, Britain, France, Germany, Japan and Russia. This research demonstrated that, in carefully controlled experiments, transition could be delayed for appreciable distances with consequent large decreases in viscous drag (compared to the turbulent level) [4].

So far, LFC technology and NLF airfoil/wing design optimization still are two main efficient methods which can reduce significantly turbulence skin friction by delaying transition location at high Reynolds numbers. It is well known that maintaining a wide range of favorable pressure gradient is an efficient way to obtain a NLF airfoil/wing. However, the existence of a long portion of favorable pressure gradient on laminar flow airfoil/wing surface leads to strong shock wave near the trailing edge of airfoil due to the recovery of pressure in transonic flow. Therefore, the reduction of the friction drag is competitively balanced with the increase of shock wave induced drag. Hence, LFC and NLF airfoil/wing design optimization in transonic regime are still in the category of a laboratory curiosity.

In paper [5], a model of NLF airfoil/wing design optimization in transonic flow is developed, i.e. delaying the transition location to maintain a larger region of favorable pressure gradient on airfoil surface, meanwhile installing an optimal Shock Control Bump (SCB) shape at the location of shock wave to reduce wave drag. Therefore the NLF airfoil design optimization in transonic regime is converted into a two-objective optimization problem: optimizing SCB shape for wave (or pressure) drag reduction, optimizing airfoil shape for delaying transition. Where, the second order numerical scheme Reynolds Averaged Navier–Stokes (RANS) simulation coupled with boundary layer analysis and linear stability prediction method is introduced in NLF airfoil design optimization since only one time of flow solver is needed, even a few times of less time-consuming sub-iterations between boundary layer analysis and transition prediction is required.

In industrial design applications, the most widely used method for stream-wise transition prediction is the e^N-database method. This is a method based on linear stability theory and experimental data. Linear stability theory states that the initial disturbances grow or decay linearly in steady laminar flow and the flow will remain laminar if the initial disturbances decay. In the derivation of linear stability equations, each flow variable is decomposed into a mean-flow term plus a fluctuation term and substitute into flow equations. Because the fluctuations are assumed to be small, their products can be neglect. With the addition of parallel flow assumption, a set of partial differential equations describing the grow or decay of the disturbances can be derived and detailed derivation can be found in [6]. In the 1950s, Van Ingen [7,8], Smith and Gamberoni [9] independently used the results from the linear stability theory and compared them with experimental data of viscous boundary layers. They found that transition from laminar to turbulent frequently happened when the amplification of disturbances calculated from stability theory reached about 8100. This corresponds to e^N where N equals to 9 and this is the well known criterion for Tollmien–Schlichting instabilities. The present authors choose the e^N-database method for transition prediction because it has been proven [10,11] to provide reasonably accurate transition locations on airfoils.

In paper [5], the equivalent two-objective optimization model for NLF airfoil/wing design is solved by using a Multi-Objective Genetic Algorithms (MOGAs) coupled with Pareto games to obtain a NLF airfoil with a larger laminar flow region and a weaker shock wave through cooperative games. But, this is time-consuming numerical procedure.

Surrogate modeling (also known as metamodeling) is a proven approach to speed up complex optimization problems by using significantly fewer function evaluations. Surrogate models are mathematical approximation models that mimic the behavior of (possibly computationally expensive) simulation codes such as mechanical or electrical finite element simulations, analytical models, or computational fluid dynamics (CFD). Singh et al. [12] coupled surrogate models (kriging, radial basis functions and support vector regression) with the efficient multi-objective optimization algorithm to identify a Pareto front of cyclone designs with a minimal number of simulations. Koziel et al. [13] demonstrated surrogate-assisted multi-objective constrained optimization of aerodynamic components using a combination of data-driven and physics-based models, design approach exploited variable-fidelity CFD models, auxiliary data-driven and response surface approximation (RSA) models (both global and local), as well as multi-objective evolutionary algorithms (MOEAs). Koziel et al. [14,15] proposed a multi-objective design procedure that allows to obtain the Pareto front based on variable-fidelity simulations and surrogate models. Leifsson and Koziel et al. [16] proposed a fast surrogate model construction method by approximating the low-fidelity CFD simulation data to reduce the computational cost of a multi objective optimization procedure, then surrogate is corrected using sparsely sampled high-fidelity CFD data and parameterized output space mapping. But it is hard to construct a surrogate model to approximate transition location in NLF shape optimization, because it is quite sensitive to the aerodynamic configurations and flow conditions. So, a novel approach based on the concept of Nash Equilibrium coupled with flow solver is used in this paper.

Over the past decade, Nash Equilibrium (NE) theory has become an efficient tool to solve Multi Criterion Optimization (MCO) problems in aerodynamics [17–20] and other relative fields [21,22]. The solution of a MCO problem can be viewed as a NE under the concept of competitive games. In the Ph.D thesis of Sefrioui [23], Nash games have been introduced and implemented with Genetic Algorithms (GAs) on analytical functions. In this paper, a distributed Nash Evolutionary Algorithms (EAs) presented in [24] is extended to multi-level parallel computing, namely multi-level Parallel Nash EAs (PNEAs). The proposed improved methodology is used to solve NLF airfoil design optimization problem high efficiently. It shows that the optimization method developed in this paper can easily capture a NE between transition delaying and wave drag increasing. Results of numerical experiments demonstrate that both wave drag and friction drag performances of the NE are greatly improved at transonic design condition. Moreover, performance of the NE is equivalent to that of Pareto front, but it is much more efficient in terms of CPU time. The results illustrate the robustness of the methodology, its efficiency in a distributed computing environment and its potential for MCO problems.