Shock Control Bump Design Optimization on Natural Laminar Aerofoil

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Abstract The chapter investigates Shock Control Bumps (SCB) on a Natural Laminar Flow (NLF) aerofoil; RAE 5243 for Active Flow Control (AFC). A SCB approach is used to decelerate supersonic flow on the suction/pressure sides of transonic aerofoil that leads delaying shock occurrence or weakening of shock strength. Such an AFC technique reduces significantly the total drag at transonic speeds. This chapter considers the SCB shape design optimisation at two boundary layer transition positions (0 and 45%) using an Euler software coupled with viscous boundary layer effects and robust Evolutionary Algorithms (EAs). The optimisation method is based on a canonical Evolution Strategy (ES) algorithm and incorporates the concepts of hierarchical topology and parallel asynchronous evaluation of candidate solution. Two test cases are considered with numerical experiments; the first test deals with a transition point occurring at the leading edge and the transition point is fixed at 45% of wing chord in the second test. Numerical results are presented and it is demonstrated that an optimal SCB design can be found to significantly reduce transonic wave drag and improves lift on drag (L/D) value when compared to the baseline aerofoil design.

1 Introduction

With rising fuel price and increasing environmental concerns, the drag reduction of transonic aircraft is emerging as one of the most important aeronautical problems. Drag reduction allows improving eco-fuel efficiency which is directly related to aircraft emissions. In other words, drag reduction saves mission operating cost and reduces critical aircraft emissions. Recent advances in design tools, materials, electronics and actuators offer implementation of flow control technologies to improve aerodynamic efficiency [1]. The use of active flow control devices on

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current transonic aircraft wing can improve aerodynamic efficiency while still using the existing airfoils or wing. Both civil and unmmaned aircraft can benefit using this active flow control technique. In this chapter, the concept of Shock Control Bump (SCB) proposed by Ashill et al. [1] is introduced and it is implemented to a natural laminar flow aerofoil RAE 5243 to reduce transonic total drag [1, 6]. Two optimisation test cases are conducted using an Euler solver with another boundary layers viscous software coupled to advanced Evolutionary Algorithms [4]; the first test considers boundary layer transition at the leading edge of RAE5243 and the second test considers the boundary layer transition at 45% of chord.

2 Methodology

The method couples the Hierarchical Asynchronous Parallel Multi-Objective Evolutionary Algorithms (HAPMOEA software) with several analysis tools. The HAPMOEA is based on the well known Darwinian principle and implemented with Evolution Strategies [4]. The core of this method incorporates the concepts of Covariance Matrix Adaptation, CMA, Distance Dependent Mutation, DDM [3]. At the top level of this method, the asynchronous parallel computation [7], multi-fidelity hierarchical topology and Pareto tournament selection are implemented. At the bottom level, the method does two major search operations (Mutation and combination) under the Pareto-game strategy. In the middle level, the method couples an evolutionary optimiser (HAPMOEA), analysis tools and a statistical design tool taking into account uncertainty. Details and validations of HAPMOEA can be found in Ref. [5].

3 Aerodynamic Analysis Tool

In this chapter the Euler–Boundary layer code MSES written by Drela [2] is utilised. The MSES software is a coupled viscous/inviscid Euler method for the analysis and design of multi-element/single-element airfoils. It is based on a streamline-based Euler discretization and a two-equation integral boundary layer formulation which are coupled through the displacement thickness and are solved simultaneously by a full Newton method. The mesh of RAE 2822 obtained by MSES consists of 213 normal direction lines and 36 streamwise lines in a bounds of $x \in [-2.0{:}3.0]$ and $y \in [-2.5{:}3.5]$. A predefined lift coefficient (C_l) can be obtained by adapting the angle of attack (α) of the aerofoil. Validation of MSES compared to wind tunnel experimental data can be found in Ref. [4].

4 Real World Design Problem

4.1 Baseline Analysis and Formulation

The baseline RAE 5243 aerofoil design is tested at the following flow conditions $M_\infty = 0.68$, $C_l = 0.82$, $Re = 19.0 \times 10^6$ according to the Ref. [6] with two

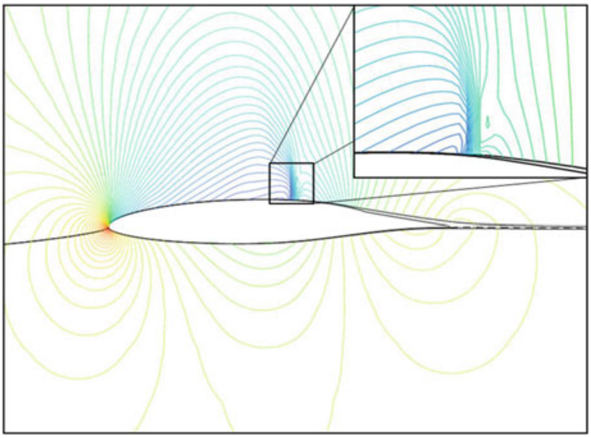

Fig. 1 Baseline at 0%c transition

boundary layer transitions at 0 and 45% of chord. Figures 1 and 2 show Cp contours obtained by MSES. It can be seen that there is strong normal shock on upper surface of baseline design at both transition conditions. The shock occurs approximately at 56.0% of chord and 60.0% of chord for 0 and 45%c of boundary layer transitions respectively. In the following sections, two SCB design optimizations are conducted to minimize the total drag (Cd_{Total}).

4.2 Problem Definition

This test case considers a single objective design optimisation of a SCB on the suction side of the RAE 5243 aerofoil to minimize Cd_{Total} at flow conditions $M_\infty = 0.68$, $C_l = 0.82$, $Re = 19.0 \times 10^6$ and with the boundary layer transitions

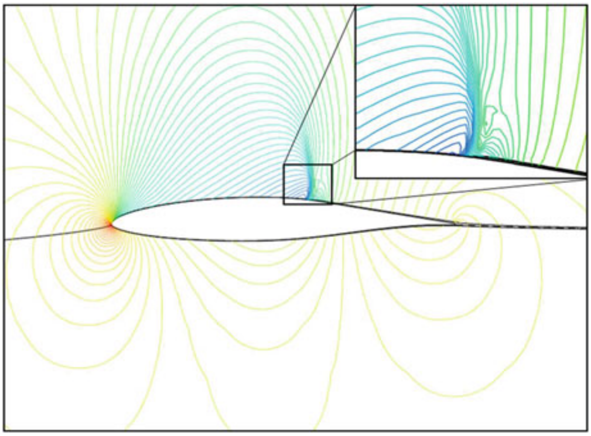

Fig. 2 Baseline at 45%c transition

at 0 and 45%c. The fitness function is shown in Eq. (1).

$$f_1 = min\,(Cd_{Total}) = min\,(Cd_{Viscous} + Cd_{Wave}) \qquad (1)$$

4.3 Design Variables

Three design variables are considered for the parameterization of the bump using a Beziers spline: SCB length (SCB_L), SCB height (SCB_H) and SCB peak position (SCB_P). The SCB_L and SCB_H are indicated as percentage of chord while the SCB_P is in percentage of SCB_L. The design bounds are; SCB_L ∈[0.0:40.0], SCB_H ∈[0.0:5.0], and SCB_P ∈[0.0:100]. The centre of SCB (50% of SCB_L) will be placed at the sonic point where the flow speed transits from supersonic to subsonic.

4.4 Numerical Results

The optimisations for both SCB at 0 and 45%c transitions are conducted using a single 4×2.8 GHz processor. As illustrated in Fig. 3, the algorithm for SCB at 0%c trasition was allowed to run for 5 h and 2,418 function evaluations to the convergence value (Cd_{Total}) 0.1115. The algorithm for SCB at 45%c tra sition was allowed to run for 5 h and 1,693 function evaluations to the convergence value (Cd_{Total}) 0.00596 as shown Fig. 4.

Table 1 compares the aerodynamic characteristics obtained by the baseline design (RAE 5243) and the baseline design with suction side SCB at both 0 and 45% laminar boundary transition conditions with constant C_l i.e. $C_l = 0.82$. Due to the geometry changes by adding SCB, the baseline design with SCB will have slightly different angle of attack to chapture the constant C_l hence it will have a different vicous drag. Applying optimal SCB on the suction side of RAE 5243 aerofoil for

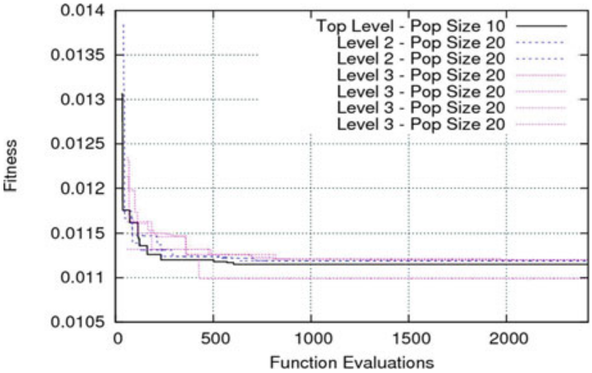

Fig. 3 Convergence at 0%c transition

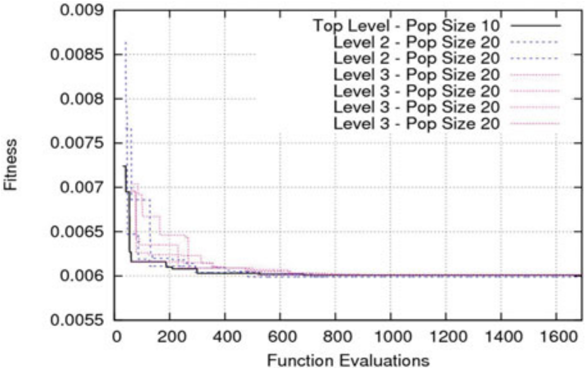

Fig. 4 Convergence at 45%c transition

Table 1 Comparison of the objectives

Description	Cd_{Total}	Cd_{Wave}	L/D
Baseline (@ 0%tran)	0.0136	0.0024	60.33
With SCB (@ 0%tran)	0.0112(−18%)	0.0006(−75%)	73.19(+21%)
Baseline (@45%tran)	0.0101	0.0032	81.72
With SCB (@45%tran)	0.0060(−40%)	0.00004(−98%)	136.57(+67%)

0% transition reduces the wave drag by 75% which leads 18% of total drag reduction. This optimal SCB improves L/D by 21.0%. Applying optimal SCB for 45% boundary layer transition reduces the wave drag by 98% which leads 40% of total drag reduction while improving L/D by 67.0%. Figures 5 and 6 show the Cp contour obtained by the optimal SCB at 0 and 45%c transition. It can be seen that there is significant drag reduction when compared to the baseline design shown in Fig. 1 and 2. It is interesting to note that the *knee shaped shock* shown in Fig. 6 for the 2D controlled flow also can be found in [6].

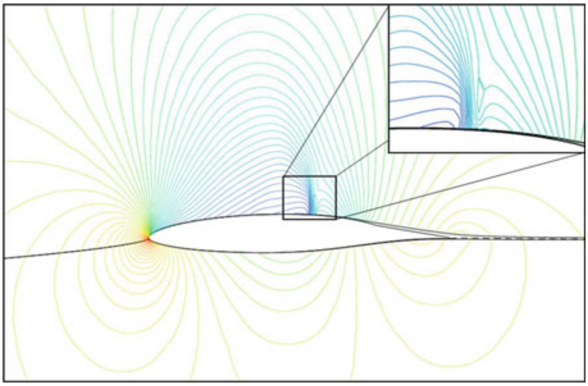

Fig. 5 Cp contour obtained by optimal SCB at 0%c trans

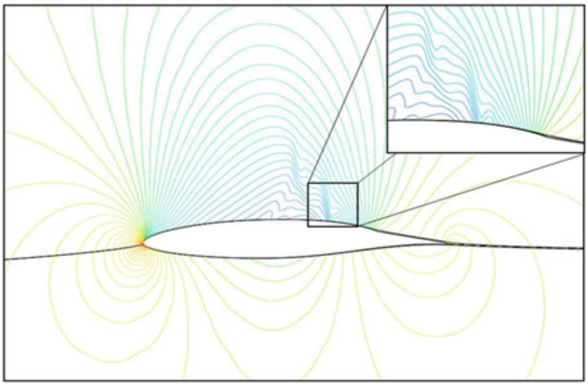

Fig. 6 Cp contour obtained by optimal SCB at 45%c trans

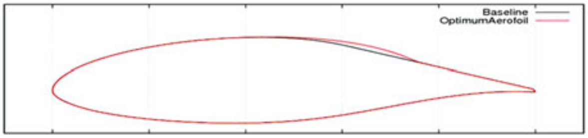

Fig. 7 Optimal SCB at 0%c tran

Figures 7 and 8 compare the geometry of the baseline design and with optimal SCB at both 0 and 45% transition conditions. The optimal SCB design (0% tran) consists of $SCB_L = 39.56\%c$, $SCB_H = 1.53\%c$ and $SCB_P = 65.8\% SCB_L$ placed between (0.3611, 0.0845) and (0.7568, 0.0453). The optimal SCB design (45% tran) consists of $SCB_L = 35.73\%c$, $SCB_H = 1.38\%c$ and $SCB_P = 67.0\%\ SCB_L$ placed between (0.4189, 0.0860) and (0.7763, 0.0417). The optimal SCB for the 45% transition is located at 5%c towards the trailing edge when compared to the optimal SCB at 0% transition due to the sonic position.

Table 2 compares the baseline aerofoil geometry to one with an optimal SCB. It can be seen that adding an optimal SCB does not change the maximum thickness of the baseline to avoid fiction drag penalty. In contrast, there is slight increment on the maximum camber and its position which is moved toward to the trailing edge by 10%c. In other words, the suction side of aerofoil becomes flatter by using a SCB when compared to the baseline design as shown Figs. 5 and 6.

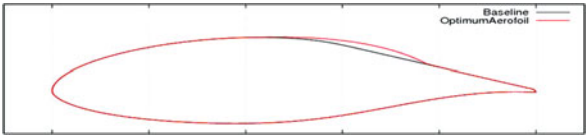

Fig. 8 Optimal SCB at 45%c tran

Table 2 Aerofoil geometry parameters

Description	Thickness_{Max}	Camber_{Max}
Baseline (@ 0%tran)	$0.14(@40\%c)$	$0.018(@54\%c)$
With SCB (@ 0%tran)	$0.14(@40\%c)$	$0.021(@63\%c)$
With SCB (@45%tran)	$0.14(@40\%c)$	$0.022(@65\%c)$

5 Conclusions

In this chapter a robust evolutionary technique has been implemented, providing a potential tool for Shock Control Bump design optimization as an effective active flow control procedure. Numerical results which are presented clearly show the benefit of using SCB techniques on current aerofoil for transonic drag reduction which will save an operating and manufacturing cost when compared to redesigning new aerofoil and wing planform shape. Future work will focus on robust Taguchi design optimization of SCB adaptive geometries which can produce the aerodynamic model with better performance and stability at uncertain operating conditions.

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