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Optimisation of adaptive shock control bumps with structural constraints

Edward Jinks, Paul Bruce *, Matthew Santer

Department of Aeronautics, Imperial College London, SW7 2AZ, UK

A R T I C L E   I N F O

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This paper presents the results from a study to design an adaptive shock control bump for a transonic aerofoil. An optimisation framework comprising aerodynamic and structural computational tools has been used to assess the performance of candidate adaptive bump geometries based on a novel surface-pressure-based performance metric. The geometry of the resultant design is a unique feature of its adaptivity; being strongly influenced by the (passive) aerodynamic pressure forces on the flexible surface as well as the (active) displacement constraints. This optimal geometry bifurcates the shock-wave and carefully manages the recovering post-shock flow to maximise pressure-smearing in the shock-region with only a small penalty in L/D for the aerofoil. Short adaptive bumps (with small imposed displacements) generally perform better than taller ones, and maintain their performance advantage for a wide range of bump positions, suggesting good robustness to variations in shock position, which are an inevitable feature of a real-world flight application. Such devices may offer advantages over conventional (fixed geometry) shock control bumps, where optimal performance is achieved with taller devices, at the expense of poor robustness to variations in shock position.

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1. Introduction

Shock control bumps (SCBs) have received considerable attention in recent years owing to their potential to reduce wave drag [1–4] or delay transonic buffet [5–7]. They work by modifying the upper surface geometry of a transonic wing in the vicinity of the shock wave to favourably impact the airflow. Previous research into SCBs has comprised a mixture of experimental and computational efforts. Computational studies have invariably looked at complete (or part) wing geometries and considered global metrics (such as the wing's lift-to-drag ratio) to assess the impact of SCBs on performance. Such studies have confirmed the performance-enhancing potential of SCBs, but concede considerable uncertainty regarding details of the fine-scale features of the flow due to resolution limitations. In contrast, experimental studies lend themselves to detailed studies to resolve the fine-scale features of the flow produced by SCBs (often in isolation), but struggle to replicate real-world (i.e. in-fight) conditions and very rarely offer global performance metrics such as L/D.

SCB performance is highly sensitive to shock position [8]. Studies of SCBs at so-called 'off-design conditions' (defined in most investigations as being when the shock wave is deemed to be upstream or downstream of its optimal location) have shown that even small variations in shock position, as would accompany minor changes in Mach number or incidence during flight, can significantly impact performance, through the appearance of undesirable expansions, secondary shock systems, and flow separations [9]. Thus, the dilemma facing wing designers is how to exploit the performance-enhancing potential of SCBs over a narrow range of shock positions (operating envelope) without incurring excessive off-design penalties. One option is to use an array of finite span (3-D) SCBs, which have been shown to be more robust to variations in shock position while still achieving an on-design performance benefit close to that of an optimal 2-D SCB [10]. Furthermore, some studies have suggested that 3-D SCBs may also delay the onset of transonic buffet (relative to a clean wing or one with a 2-D SCB), and thus offer potential for enhancing off-design wing performance [6,11].

Another option is to design an SCB with the ability to respond to the flow-field in the control region to avoid any detrimental off-design behaviour and maintain global aerofoil characteristics such as lift and drag coefficients. The concept of an adaptive SCB is not new [1], however the addition of adaptivity brings with it a structural aspect that has not been evaluated in great detail with only a handful of studies having even begun to look at this aspect [12–14]. In contrast, the aero-structural behaviour of transonic wings is well characterised and designing a wing surface that is

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* Corresponding author.
E-mail address: p.bruce@imperial.ac.uk (P. Bruce).

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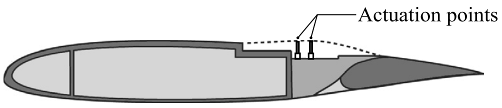

Fig. 1. Illustration of expected actuator loading and initial sizings. Adapted from [1].

stiff enough to withstand aerodynamic loading without excessive deflections is a straightforward task. Thus, the integration of an adaptive SCB into a transonic wing presents a unique challenge: a requirement for sufficient surface flexibility to allow useful deflections without sacrificing the global structural integrity of the wing or compromising critical control surfaces such as flaps.

Little is known about the relative merits of active (e.g. actuator-driven) vs. passive (e.g. pressure-induced) adaptivity for SCBs. The latter potentially offers significant advantages in terms of reduced complexity and easier integration. Some passive effects are inevitable even with an actively controlled system: a material flexible enough to deform under mechanical actuation will also be susceptible to the significant surface pressure gradients present near the shock wave on the upper surface of a transonic wing. For these reasons, a multi-disciplinary (coupled aero-structural) approach is required to explore the potential of adaptive SCBs, whether actively or passively deployed. The aero-structural behaviour of a flexible surface in a high speed flow is not a topic that has received a great deal of attention in the literature, and those studies that do exist tend to focus on purely supersonic canonical geometries [15–17]. While these studies have unquestionably shed light on the behaviour of flexible surfaces, including the conditions for the onset of instabilities (i.e. panel flutter), it is not clear how such results apply to transonic flows, where the boundary conditions are significantly different.

In this investigation, we study an adaptive SCB in the presence of a strong transonic shock wave on a conventional RAE-2822 supercritical aerofoil. This acknowledges the fact that SCBs offer significant potential as an enabling technology for applications where strong transonic shocks are present. We will show, through a parametric study using aero-structural optimisation based on a novel performance metric, that adaptive SCBs offer unique performance-enhancing characteristics when implemented on a transonic wing. This work ultimately serves as a framework to explore the unique characteristic behaviour of adaptive SCBs and learn how to design with them. In this context, the main contributions of this study are summarised as: (1) Implementation of an optimisation framework that enables optimal adaptive SCB designs for the RAE-2822 aerofoil; (2) Definition of a performance metric to assess the potential of adaptive SCBs beyond simply reducing wave drag or managing boundary layer separation; (3) Developing our understanding of the unique behaviour of adaptive SCBs and their performance-enhancing potential; (4) Exploring the performance envelope of adaptive SCBs through the consideration of sub-optimal designs.

2. Optimisation framework

In this section we describe the developed aero-structural framework which combines aerodynamic and structural analysis within an optimisation loop for 2D adaptive SCBs. The design is based on the original concept of [1] as illustrated in Fig. 1. In this concept a region of compliant skin on the suction surface of a supercritical aerofoil in the expected region of the normal shock is actuated at multiple discrete locations. This actuation results in structural deformation of the skin which, in combination with the effect of aerodynamic pressure results in a bump geometry being formed. The optimisation process proceeds according to the flow chart illustrated in Fig. 2 until an "optimal" geometry is reached. In this context, we use the term "optimal" to describe the converged solution of our defined optimisation problem, each aspect of which will now be discussed in detail.

2.1. Structural modelling

We first consider the structural modelling of the flexible section of the aerofoil's upper surface. This section is modelled as a simple rectangular plate with dimensions 200 × 150 mm (stream-wise length × span-wise width) using a finite element approach. These dimensions were selected to match the parameters used in a related experimental study in a high speed wind tunnel, the results of which are reported elsewhere [18]. The stream-wise length of the flexible region (200 mm) corresponds to a bump length $l_b = 0.2c$ for a nominal aerofoil chord of 1 m. Full fixation against translation and rotation is imposed on the upstream and downstream ends of the flexible region. The two sides of the region are unconstrained. Actuation points are modelled as line displacements which remain constant across the span. These actuation lines are controlled via displacement rather than actuation force. This is both to facilitate numerical convergence, and also to allow straightforward comparison with the typical aerodynamic approach of existing static SCB designs which stipulate SCB height.

The commercial solver Abaqus [19] is used to perform a geometrically nonlinear, quasi-static analysis using a Newmark Algorithm with adaptive time stepping. Linearly spaced quadratic elements with uniformly reduced integration (S4R) were adopted. The rectangular nature of the test piece ensured a very high quality mesh was produced with zero non-orthogonality. The solver was validated against the known analytical solution of a beam in bending for a 2 mm out-of-plane displacement that remained constant across the span. The variation of the maximum von Mises stress with the total number of elements is presented in Fig. 3. A mesh size of 3×10^4 elements was selected for use in this study.

2.2. Aerodynamic modelling

The design cruise conditions for the RAE-2822 aerofoil chosen for this study are $M_{design} = 0.73$ at $\alpha = 3.19$, $Re = 6.5 \times 10^6$ [20]. This causes an upper surface shock strength of $M_{shock} = 1.25$ with a location of $x/c \approx 0.495$. By selecting this single on-design case for aerodynamic analysis, the design space is reduced significantly which lends itself to design optimisation.

2.2.1. CFD meshing

With many previous optimisation studies for static SCBs, the design space and the control parameters used to define the geometries are well known. The variation between existing designs is small which means that meshing a design for a given set of control parameters results in similar meshes for the majority of test cases. The similarity between each mesh allows for the construction of a case-specific meshing tool that can handle the small differences associated with each SCB design. A structured mesh requires a rigorous grid to be calculated for each case however the subtle differences between subsequent iterations mean that the development of a structured mesh generation algorithm is a beneficial option that allows many controls to be put in place, thus ensuring high quality meshes.

The mesh is constructed with the use of transfinite interpolation schemes as well as elliptic smoothing between the aerofoil surface and the bounds of the domain. The former is predominantly used to initialise the grid based upon the bounding conditions specified by the user. For this case a standard C-mesh is used to allow the flow to become established upstream of the aerofoil and to monitor the wake downstream. The overall extent of the mesh is shown in Fig. 4a.

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