Adaptive Bump Aerodynamic Configuration Optimization and Structural Conceptual Design Postprint

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Abstract

Supercritical airfoils develop shock waves when the freestream velocity exceeds the critical Mach number, resulting in a rapid increase in wave drag. To mitigate wave drag across various flight conditions, this study investigates shock control bumps. By integrating NURBS curve modeling and CFD simulation modules, a bump simulation and optimization platform was established for the optimization of bump configurations under diverse flow field conditions. Using the RAE2822 airfoil as a computational example, results demonstrate that under off-design conditions, the optimized bump configuration can substantially reduce airfoil wave drag and enhance aerodynamic efficiency at off-design points. To address the issue of limited effective drag reduction range associated with single-point optimized bumps, a two-dimensional adaptive bump design concept based on shape memory alloys is proposed. The adaptive bump can adjust its configuration in response to temperature to control shock waves under varying flow field conditions.

Full Text

Aerodynamic Configuration Optimization and Structural Concept Design of Adaptive Bump

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Abstract

When the inflow velocity exceeds the critical Mach number, supercritical airfoils develop shock waves that cause rapid increases in wave drag. To reduce wave drag under different flight conditions, this paper investigates shock control bumps. An optimization platform integrating NURBS curve modeling and CFD simulation modules was developed to optimize bump configurations across various flow conditions. Using the RAE2822 airfoil as a test case, results demonstrate that the optimized bump configuration substantially reduces airfoil wave drag and improves aerodynamic efficiency at off-design points. To overcome the narrow effective range of single-point optimized bumps, a two-dimensional adaptive bump design concept based on shape memory alloys is proposed. The adaptive bump can adjust its configuration according to temperature, enabling shock control across different flow conditions.

Keywords: wave drag; shock control bump; adaptive bump; shape memory alloy; NURBS curve

Introduction

Analyses indicate that global air traffic volume in 2025 will increase two- to three-fold compared to current levels. According to the U.S. "Next Generation Air Transportation System (NextGen)" program, advanced civil aircraft scheduled for service in 2030-2035—the N+3 generation—must achieve significant improvements in emissions, fuel consumption, and operating costs [1]. At high subsonic flight speeds, local shock waves appear on wings and fuselages, with shock intensity increasing rapidly as flight velocity rises. Boeing research shows that next-generation civil aircraft featuring blended wing body (BWB) configurations, compared to conventional fuselage-plus-wing designs, promise to simultaneously meet technical requirements for noise and fuel consumption reduction. However, studies indicate that BWB configurations experience significantly increased shock drag, exceeding 10% of total drag [2]. Consequently, airfoil shock control and drag reduction technologies hold strong application potential.

The shock control bump represents a typical flow control technique for shock wave management. Existing research demonstrates that solid bumps can significantly weaken shock intensity and reduce shock drag without adding viscous drag [3-6]. Numerous aviation research institutions worldwide have investigated the shock drag reduction characteristics of bumps. In 1992, Ashill et al. first proposed the concept of using bumps on laminar flow airfoils to reduce shock drag [7]. NASA Langley Research Center conducted wind tunnel experiments on airfoils with fixed bumps under high subsonic conditions at off-design points, revealing that proper bump configuration selection can reduce airfoil drag by 12-15% [8]. K.H. Lo et al. from the University of Glasgow studied three-dimensional bump configurations for flow separation control under supersonic conditions

(Mach=1.3), demonstrating that the injection pressure from three-dimensional bumps effectively controlled flow direction and spanwise separation [9]. Jeremy P. Eastwood et al. from Cambridge University investigated three-dimensional bump configuration design, analyzing the influence of different design parameters on drag reduction effectiveness [10].

Multiple studies on bump drag reduction have shown that fixed bumps suffer from narrow operating bandwidths, limiting practical application. Researchers have consequently proposed adaptive bump design concepts that automatically adjust bump configuration according to flight state to meet varying operational requirements. E. Jinks et al. studied a single-point actuated aluminum adaptive bump structure, demonstrating that adaptive bumps can optimize multiple mission states and maintain favorable aerodynamic characteristics across a broader flight envelope [11]. Canadian researchers A.V. Popov and M. Labib investigated distributed actuation for adaptive bump deformation control, analyzing actuator control methods and deformation driving forces during bump shape changes [12].

This paper targets shock drag reduction for supercritical airfoils, combining NURBS curve modeling and CFD simulation methods to investigate bump position optimization and configuration optimization under different flow conditions for RAE2822 supercritical airfoils. Based on these studies, a structural implementation concept for adaptive bumps is proposed.

1. NURBS Curve Parameterization and Optimization Methodology

1.1 NURBS Curve Formulation

To obtain bump geometries under different aerodynamic conditions, spline curves are employed for parametric bump modeling. Common parametric curve design methods include Bezier curves, B-splines, and NURBS (Non-Uniform Rational B-Splines) [13], which generate target geometric models from control points. NURBS curves exhibit excellent local support properties—modifying a single control point affects only the corresponding local curve segment—enabling local geometry modification [14]. This paper selects NURBS curves for bump parameterization, implementing adaptive bump configuration modeling through MATLAB programming.

A p-degree NURBS curve is typically defined using parameter u as:

$$C(u) = \frac{\sum_{i=0}^{n} N_{i,p}(u)\omega_i P_i}{\sum_{i=0}^{n} N_{i,p}(u)\omega_i}$$

where $P_i(x_i, y_i)$ are control points (forming the control polygon), ω_i are weight factors defining control point weights, and $n+1$ weight factors correspond to an equal number of control points. The terms $N_{i,p}(u)$ are p-degree B-spline basis functions obtained from the knot vector U according to recursive relations. The knot vector $U = \{u_0, u_1, \cdots, u_m\}$ consists of a sequence of real numbers, where u_i are knot values and $m = n + p + 1$. This paper employs uniform knot vectors.

Thus, specifying a set of control point coordinates (x_i, y_i), curve degree, and individual control point weights uniquely defines a NURBS curve. As shown in [Figure 1: see original paper], a cubic NURBS curve generated using four control points with unit weights is presented. In the figure, for Curve 01, control point 2 has a Y-coordinate of 0.5, while for Curve 02, control point 2 has a Y-coordinate of 1.0. The results demonstrate that modifying control point coordinates enables local shape adjustment.

1.2 Shock Control Bump Configuration Optimization Method

To obtain optimal bump configurations for specific flow conditions, this paper employs a genetic algorithm to optimize NURBS curve parameters for the bump. CFD simulation provides aerodynamic characteristic parameters (lift coefficient, drag coefficient, lift-to-drag ratio, etc.). The optimization seeks bump configurations with minimum drag coefficient while maintaining lift coefficient constraints.

Using the Isight multidisciplinary simulation optimization platform, MATLAB bump curve generation, Gambit mesh updating, and Fluent aerodynamic parameter calculation modules are integrated with the GA-II genetic optimization algorithm to achieve bump configuration optimization across different flow states. The flow chart is shown in [Figure 2: see original paper].

1.3 CFD Reliability Verification

CFD simulation technology is widely applied in active and passive flow control research. This paper utilizes Fluent fluid simulation software to investigate the aerodynamic characteristics of RAE2822 airfoil with shock control bumps. For validation purposes, the transonic flow computation capability is verified using the RAE2822 airfoil.

Computation conditions: Mach number $Ma = 0.729$, angle of attack $AOA = 2.31^\circ$, Reynolds number $Re = 6.49981 \times 10^6$.

Table 1 compares Fluent results with experimental data. The Spalart-Allmaras (S-A) model overpredicts drag while the $k - \omega$ SST model underpredicts lift. Considering computational time and accuracy requirements for the iterative optimization process, the S-A model is selected for subsequent calculations with 59,800 grid cells and a first-layer grid height of 6.3×10^{-5}.

Table 1 Comparison of calculation and experimental results for RAE2822 airfoil

Grid number	Model	C_L	C_D
59800	S-A	0.703	0.0139

Grid number	Model	C_L	C_D
59800	SST	0.695	0.0135
Experiment	-	0.703	0.0127

The pressure coefficient distribution obtained from the S-A model shows good agreement with NASA wind tunnel test results, as illustrated in [Figure 3: see original paper]. The computational methodology is therefore validated as reliable.

2. Shock Control Bump Position Selection

Different bump deformation regions and shapes produce varying aerodynamic effects. To determine an appropriate local bump deformation region, three different optimization intervals near the shock wave position on the airfoil upper surface are selected for evaluation: Case 1, Case 2, and Case 3, as shown in [Figure 4: see original paper]. The deformation interval parameters are listed in Table 2. Simulation conditions match those in Section 1.3, using the RAE2822 supercritical airfoil.

Table 2 Bump configuration optimization interval parameters

Case	Start (x/c)	End (x/c)
Case 1	0.35	0.55
Case 2	0.42	0.65
Case 3	0.50	0.70

The optimized lift and drag coefficients are presented in Table 3. All cases exhibit drag reduction to varying degrees. Case 2 demonstrates the best drag reduction performance, decreasing drag coefficient by approximately 6.15% while increasing lift coefficient by only 1.59%, resulting in an 8.25% improvement in lift-to-drag ratio—significantly superior to Case 1 and Case 3.

Table 3 Aerodynamic characteristics under different optimal conditions

Case	C_D	C_L	L/D	ΔC_D	ΔC_L	$\Delta(L/D)$
Original	0.0139	0.703	50.6	-	-	-
Case 1	0.0137	0.704	51.4	-1.75%	+0.17%	+1.95%
Case 2	0.0131	0.715	54.6	-6.15%	+1.59%	+8.25%
Case 3	0.0135	0.710	52.7	-3.16%	+0.96%	+4.25%

The pressure coefficient distributions in [Figure 6: see original paper] reveal that all optimized results transform the initial strong shock into a weaker shock, demonstrating that surface deformation successfully mitigates shock strength. For Case 1, shock position remains largely unchanged compared to the baseline airfoil with similar pressure distributions. Cases 2 and 3 show significant shock weakening and shock position movement relative to the original airfoil.

Based on these results, optimal drag reduction occurs when the shock position is near the bump deformation region center (Case 2). When the shock is located forward of the bump center (Case 3), some effectiveness remains. When the shock is positioned aft of the bump center (Case 1), drag reduction is minimal.

3. Aerodynamic Characteristics Under Variable Conditions

3.1 Influence of Angle of Attack Variation

The adaptive bump design objective is enabling aircraft to alter bump configuration in real-time according to flight state, ensuring optimal wing aerodynamic characteristics across required flight conditions. Therefore, bump configurations must be optimized for various aerodynamic states to generate a family of bump shape curves.

Using variable angle of attack as an example, bump curves for different aerodynamic states are obtained by optimizing at $AOA = 1.8^\circ$, 2.31°, and 2.8° within the Case 2 region. Simulation conditions match Section 1.3 using the RAE2822 airfoil. As shown in [Figure 7: see original paper], bump height increases with optimization angle of attack, with maximum height variation less than 3%.

Table 4 Aerodynamic characteristics under different optimal conditions

AOA	Baseline C_D	Baseline C_L	Bump C_D	Bump C_L	ΔC_D	ΔC_L	$\Delta(L/D)$
1.8°	0.0116	0.610	0.0116	0.613	-0.55%	+0.51%	+1.07%
2.31°	0.0139	0.703	0.0131	0.715	-6.15%	+1.59%	+8.25%
2.8°	0.0176	0.790	0.0158	0.804	-10.28%	+1.78%	+13.44%

At small angles of attack ($AOA = 1.8^\circ$), no significant shock wave exists on the airfoil upper surface, resulting in minimal bump deformation and negligible impact on aerodynamic characteristics (lift and drag coefficient changes $< 1\%$). As angle of attack increases ($AOA = 2.31^\circ$, 2.8°), stronger shock waves develop and bumps demonstrate pronounced drag reduction, decreasing drag by 6.15% and 10.28% respectively. Bump height also increases with angle of attack.

The drag polar in [Figure 8: see original paper] shows that bumps increase drag outside the design region but improve baseline airfoil drag characteristics within the design region. [Figure 9: see original paper] illustrates that lift-to-drag ratio improves substantially compared to the baseline airfoil at angles of attack above the optimization condition. However, for a given optimization result, aerodynamic performance degrades relative to the baseline when the angle of attack is below the optimization condition.

Investigating optimization results across multiple angles of attack, [Figure 10: see original paper] presents optimized airfoil aerodynamic characteristics. The results show that optimizing bump configuration at various angles of attack yields significant lift improvements at high angles of attack, with maximum lift-to-drag ratio increasing by 4.4% and the optimal L/D angle shifting from 1.8° to 2.4°. Compared to the clean RAE2822 airfoil, the optimized bump configurations enable higher lift-to-drag ratios across a broader angle of attack range (1.8°-2.6°). The corresponding maximum bump deformation height shown in [FIGURE:10(b)] reveals negligible deformation below 1.8° (the baseline' s optimal L/D condition), while deformation height increases approximately linearly with angle of attack above 1.8°, producing substantial aerodynamic benefits.

Thus, adaptive bumps that vary with flight state can deform as needed to ensure optimal airfoil aerodynamic characteristics across a wide operating range.

3.2 Aerodynamic Characteristics at Off-Design Points

During flight, aircraft experience rapid state changes due to gusts and other factors, necessitating investigation of a single bump configuration's aerodynamic performance across different conditions. [Figure 11: see original paper] presents lift coefficient and lift-to-drag ratio at $AOA = 1.8^\circ$, 2.31°, and 2.8° ($Ma = 0.729$) for airfoils optimized at different angles of attack, with bump height represented by Y/C.

Design point optimization results (marked by black circles) show minimal lift coefficient variation but maximum lift-to-drag ratio, indicating substantial drag reduction. When bump height is below the optimal design value, lift coefficient remains essentially unchanged while lift-to-drag ratio improves modestly compared to the baseline. When bump height exceeds the optimal value, both lift coefficient and lift-to-drag ratio decrease rapidly. Therefore, drag reduction is only achieved when bump height is less than or equal to the optimal value.

Examining airfoils optimized at $AOA = 1.8^\circ$, 2.31°, and 2.8° operating at $AOA = 2.31^\circ$, $Ma = 0.729$, [Figure 12: see original paper] shows pressure coefficient distributions and aerodynamic characteristic variation rates. The 2.31° optimization (optimal bump height) yields the best performance with 6.15% drag reduction. The 1.8° optimization (suboptimal height) provides minimal improvement at 2.31°, reducing drag by only 2.51%. The 2.8° optimization (excessive height) severely degrades performance at 2.31°, creating a first shock upstream of the bump and a second strong shock downstream that increases drag by 23.1%.

Consequently, actively deformable adaptive bumps that can change configuration in real-time represent an effective solution for maximizing drag reduction without compromising lift characteristics.

4. Shock Control Bump Drag Reduction Mechanism

Modern supercritical wing design aims for shock-free pressure distributions at the design point. However, conventional fixed airfoils maintain this characteristic only within a narrow flight envelope. As speed or angle of attack increases, strong shocks appear on the wing surface. Appropriate bump shapes can modify local airfoil geometry to reduce wave drag. Research on shock control bumps (SCB) identifies two primary mechanisms: (1) λ-shock drag reduction and (2) isentropic compression drag reduction, corresponding to different bump configurations.

The NURBS curve parameterization constrains control points to ensure smooth transitions between the bump and baseline airfoil, producing a concave-convex-concave configuration that operates via isentropic compression principles. As flow passes over the continuously smooth bump surface, the flow direction changes gradually, generating numerous weak compression waves that coalesce into a weaker oblique shock [15]. This process extends the isentropic compression region on the airfoil upper surface, enabling more gradual flow compression, weakening shock intensity, and reducing wave drag [16].

As shown in [Figure 13: see original paper], drag reduction effectiveness strengthens with changing optimization conditions (variable angle of attack), primarily reducing shock drag component. At $AOA = 2.8^\circ$, [Figure 14: see original paper] velocity contours demonstrate that adaptive bumps significantly improve off-design aerodynamic characteristics. The optimized bump extends the isentropic compression region on the upper surface, compressing the flow more gradually and shifting the shock position from 56% chord to 62% chord while reducing shock strength.

5. Adaptive Bump Structural Design

5.1 Adaptive Bump Design Principle

Shape memory alloys (SMA) exhibit unique shape memory effects [17,18] and are widely used in industrial applications. Specialized heat treatment produces two-way memory effect materials that can continuously deform between high-temperature and low-temperature configurations under temperature control [19,20].

Leveraging SMA two-way shape memory effects enables adaptive bump structural design. As illustrated in [Figure 15: see original paper], active bump deformation relies on three components: (1) SMA skin forming the bump, (2) SMA heating devices (electromagnetic induction heating, etc.), and (3) SMA cooling (air cooling).

5.2 SMA Bump Deformation Simulation

To investigate adaptive bump structural feasibility, SMA ribbon simulations are conducted using the Lagoudas three-dimensional phenomenological constitutive model [21-23]. Structural deformation is described through elastic strain, thermal expansion strain, and phase transformation-induced strain. The simulation flow chart is shown in [Figure 16: see original paper].

Table 1 Shape memory alloy material parameters

Parameter	Value
Ribbon dimensions (undeformed)	140 × 20 × 0.5 mm
Austenite start temperature (A_s)	295 K
Austenite finish temperature (A_f)	315 K

As shown in [Figure 17: see original paper], the SMA ribbon simulation applies fixed boundary conditions at both ends with a pre-strain of -0.01 along the length direction. Temperature loading ranges from 290 K to 350 K to ensure a complete phase transformation cycle (martensite to austenite). [Figure 18: see original paper] presents maximum deflection versus temperature during reverse transformation. Results show the SMA ribbon achieves maximum deflection of 4.4% of its length. Deformation varies approximately linearly between the reverse transformation start temperature A_s (295 K) and finish temperature A_f (315 K), demonstrating excellent controllability.

6. Conclusions

1. NURBS curves parameterize adaptive bumps, and an Isight-based optimization platform integrating MATLAB bump generation, Gambit mesh updating, and Fluent flow solving enables genetic algorithm optimization.
2. The bump optimization platform investigated RAE2822 airfoil drag reduction at different bump positions, identifying the optimal deformation region. Results indicate best performance when the shock is located at the bump center. For RAE2822, the optimal adaptive bump position is 42%-65% chord.
3. Optimal bump configurations for RAE2822 were obtained at various angles of attack. Drag reduction becomes more pronounced with increasing angle of attack: 6.15% at $AOA = 2.31^\circ$ and 10.28% at $AOA = 2.8^\circ$.
4. To maximize drag reduction without affecting lift characteristics, actively deformable adaptive bumps that change configuration in real-time according to aerodynamic requirements are necessary.
5. An adaptive bump design based on shape memory alloy materials is proposed. Three-dimensional SMA constitutive modeling simulations demon-

strate 4.4% maximum deformation, with deformation varying approximately linearly with temperature during phase transformation, theoretically satisfying adaptive bump deformation requirements.

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Note: Figure translations are in progress. See original paper for figures.