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 reduce wave drag under various flight conditions, this study investigates shock control bumps. A bump simulation and optimization platform was established by integrating NURBS curve modeling and CFD simulation modules to optimize bump configurations under different flow field conditions. Using the RAE2822 airfoil as a computational example, the results indicate that under off-design conditions, the optimized bump configuration can substantially reduce airfoil shock drag and enhance aerodynamic efficiency at off-design points. To address the limited effective range of drag reduction for 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 to control shock waves under different flow field conditions.

Full Text

Preamble

Aerodynamic Configuration Optimization and Structural Concept Design of Adaptive Bump

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Abstract: Supercritical airfoils develop shock waves when the inflow velocity exceeds the critical Mach number, leading to 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 was developed to optimize bump configurations for various flow conditions. Using the RAE2822 airfoil as a test case, results demonstrate that optimized bump configurations can substantially reduce airfoil wave drag and improve aerodynamic efficiency at off-design conditions. 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 to control shock waves under different flow conditions.

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

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1. Parameterization and Optimization Methodology

1.1 NURBS Curve Parameterization

To model bump geometries under various aerodynamic conditions, spline curves are employed for parametric modeling. Common parametric curve design methods include Bezier curves, B-splines, and NURBS (Non-Uniform Rational B-Splines), which generate target geometric models based on control points. NURBS curves exhibit excellent local support properties—modifying a single control point only affects the local curve region, enabling localized geometric modifications. This study adopts NURBS curves for bump parameterization, implementing adaptive bump configuration modeling through MATLAB programming.

A p-degree NURBS curve is defined by 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 the influence of each control point, and $N_{i,p}(u)$ are p-degree B-spline basis functions derived from the knot vector $U = \{u_0, u_1, \cdots, u_m\}$ through recursive relations. The knot vector consists of a sequence of real numbers, with u_i representing knot values. This study employs a uniform knot vector.

Thus, by specifying a set of control point coordinates, curve degree, and control point weights, a NURBS curve can be generated. As shown in [Figure 1: see original paper], a 3-degree NURBS curve is created using four control points with unit weights. When the Y-coordinate of control point 2 changes from 0.5 to 1.0, the curve shape changes accordingly, demonstrating that modifying control point coordinates enables local shape adjustment.

1.2 Shock Control Bump Configuration Optimization

To obtain optimal bump configurations for specific flow conditions, a genetic algorithm is used to optimize NURBS curve parameters. CFD simulations provide aerodynamic characteristics (lift coefficient, drag coefficient, lift-to-drag ratio, etc.). The optimization seeks bump configurations with minimum drag coefficient while maintaining the lift coefficient.

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

1.3 CFD Reliability Verification

CFD simulation is widely applied in active and passive flow control research. This study uses Fluent software to investigate the aerodynamic characteristics of RAE2822 airfoil with shock control bumps. For validation, the transonic flow computation capability is verified using the RAE2822 airfoil at Mach number Ma = 0.729 and angle of attack AOA = 2.31°, with Reynolds number Re = 6.49981×10 .

compares Fluent results with experimental data. The Spalart-Allmaras (S-A) model yields slightly higher drag predictions, while the k- SST model produces slightly lower lift predictions. Considering computational time and accuracy 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 .

The pressure coefficient distribution from the S-A model shows good agreement with NASA wind tunnel test results, confirming the reliability of the flow field computation method.

2. Shock Control Bump Location 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 location on the airfoil upper surface are selected: Case 1, Case 2, and Case 3, as shown in [Figure 4: see original paper]. The deformation interval parameters are listed in .

Simulation conditions match Section 1.3, using the RAE2822 supercritical airfoil. The optimized lift and drag coefficients are presented in . All cases demonstrate drag reduction, with Case 2 showing the best performance: drag coefficient decreases by approximately 6.15% while lift coefficient increases by only 1.59%, resulting in an 8.25% improvement in lift-to-drag ratio—significantly better than Cases 1 and 3.

The pressure coefficient distributions in [Figure 6: see original paper] reveal that all optimized cases transform the original strong shock into a weaker one. Case 1 shows minimal change in shock location and pressure distribution compared to the baseline airfoil. Cases 2 and 3 exhibit significant shock weakening and shock position movement. The results indicate optimal drag reduction occurs when the shock position is near the center of the bump deformation region (Case 2). When the shock is located forward of the center (Case 3), some effect remains, but when positioned aft of the center (Case 1), drag reduction is minimal.

3. Aerodynamic Characteristics Under Variable Conditions

3.1 Effect of Angle of Attack Variation

The adaptive bump design objective is to enable real-time configuration changes according to flight conditions, ensuring optimal wing aerodynamic characteristics. This requires optimizing bump configurations across different aerodynamic states to obtain a family of bump shapes.

Using variable angle of attack as an example, optimizations are performed at AOA = 1.8°, 2.31°, and 2.8° within the Case 2 region. As shown in [Figure 7: see original paper], bump height increases with optimization angle of attack, with maximum height variation less than 3%.

The optimized aerodynamic performance across angles of attack is illustrated in [Figure 8: see original paper] and [Figure 9: see original paper]. At low angles (AOA = 1.8°), where no significant shock exists, the optimized bump is small and has minimal impact on aerodynamic characteristics (changes $< 1\%$). As angle of attack increases (AOA = 2.31°, 2.8°), stronger shocks develop and the bump demonstrates clear drag reduction: drag coefficient decreases by 6.15% and 10.28% respectively, with bump height increasing accordingly.

The drag polar in [Figure 8: see original paper] shows that bumps increase drag in non-design regions but improve drag characteristics in design regions. [Figure 9: see original paper] indicates that at angles greater than the optimization angle, the lift-to-drag ratio improves significantly compared to the baseline airfoil. However, when the angle of attack is lower than the optimization angle, aerodynamic performance degrades relative to the baseline.

Examining optimization results across multiple angles in [Figure 10: see original paper], the maximum lift-to-drag ratio increases by 4.4% and occurs at a higher angle of attack (2.4° vs. 1.8°). The optimized airfoil maintains higher lift-to-drag ratios than the baseline across a range of 1.8°-2.6°. The bump deformation height is negligible below 1.8° but increases approximately linearly with angle of attack above this threshold, corresponding to significant aerodynamic improvements.

These results demonstrate that adaptive bumps capable of changing with flight conditions can maintain optimal aerodynamic performance across a wide operating envelope.

3.2 Off-Design Aerodynamic Characteristics

During flight, atmospheric gusts can cause rapid changes in flight conditions, necessitating investigation of a single bump configuration’ s performance across different conditions. [Figure 11: see original paper] shows lift coefficient and lift-to-drag ratio for bumps optimized at different angles of attack when operated at AOA = 1.8°, 2.31°, and 2.8° at Mach 0.729, with bump height represented by Y/C.

At design points (marked by black circles), lift coefficient changes minimally while lift-to-drag ratio reaches its maximum, indicating substantial drag reduction. When bump height is less than optimal, lift coefficient remains essentially unchanged while lift-to-drag ratio improves modestly. When bump height exceeds optimal, 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.

[Figure 12: see original paper] examines pressure coefficient distribution and aerodynamic characteristic variations for bumps optimized at AOA = 1.8°, 2.31°, and 2.8° when operated at AOA = 2.31°, Mach 0.729. The bump optimized at 2.31° (optimal height) achieves the best performance with 6.15% drag reduction. The bump optimized at 1.8° (sub-optimal height) provides minimal improvement (2.51% drag reduction). The bump optimized at 2.8° (excessive height) generates a first shock ahead of the bump and a second strong shock behind it, degrading aerodynamic performance and increasing drag by 23.1%.

Thus, 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 airfoils are designed for shock-free pressure distributions at the design point. However, due to fixed airfoil geometry, this shock-free characteristic can only be maintained within a narrow flight envelope. As speed or angle of attack increases, strong shocks appear on the wing surface. An appropriately shaped bump can modify the local airfoil configuration to reduce wave drag. Research on shock control bumps (SCB) identifies two primary mechanisms: (1) -shock drag reduction and (2) isentropic compression drag reduction, corresponding to different bump configurations.

In this study, constraints on NURBS control points ensure smooth transitions between the bump and original airfoil, creating a concave-convex-concave bump configuration that operates via isentropic compression principles. As flow passes over the continuous smooth bump surface, the flow direction changes gradually, generating numerous weak compression waves that coalesce into a weaker oblique shock. This process increases the isentropic compression region on the upper surface, providing more complete flow compression, weakening shock intensity, and reducing wave drag.

As shown in [Figure 13: see original paper], drag reduction becomes more pronounced with changing optimization conditions (variable angle of attack), primarily reducing shock drag components. At AOA = 2.8°, [Figure 14: see original paper] demonstrates that the optimized bump significantly improves off-design aerodynamic characteristics by increasing the isentropic compression zone, moving the shock location from 56% to 62% chord and reducing shock strength.

5. Adaptive Bump Structural Design

5.1 Design Principle

Shape memory alloys (SMA) exhibit unique shape memory effects and are widely used in industrial applications. Through specialized heat treatment, two-way shape memory effect can be achieved, enabling structures to deform continuously between high-temperature and low-temperature configurations under temperature control.

Utilizing this two-way shape memory effect enables adaptive bump 结构设计. As shown in [Figure 15: see original paper], active bump deformation relies on three components: (1) SMA skin forming the bump, (2) SMA heating devices (e.g., electromagnetic induction heating), and (3) SMA cooling (air cooling).

5.2 SMA Bump Deformation Simulation

To investigate the feasibility of SMA adaptive bump structures, simulations are performed on SMA strips using the Lagoudas three-dimensional phenomenological constitutive model, which describes structural deformation through elastic strain, thermal expansion strain, and phase transformation-induced strain. The simulation flowchart is shown in [Figure 16: see original paper].

SMA material parameters are listed in Table 1. The undeformed strip dimensions are 140×20×0.5 mm. Boundary conditions are fixed at both ends with a pre-strain of -0.01 in the longitudinal direction. Temperature loading ranges from 290K to 350K to ensure a complete phase transformation cycle (martensite to austenite).

[Figure 17: see original paper] shows the finite element simulation results at 295K and 350K. [Figure 18: see original paper] presents the maximum deflection during reverse transformation versus temperature. The SMA strip achieves a maximum deflection of 4.4% of its length, with approximately linear deformation between the transformation start temperature As (295K) and finish temperature Af (315K), demonstrating good controllability.

6. Conclusions

(1) NURBS curves are used for adaptive bump parameterization. An optimization solver is developed by integrating MATLAB bump generation, Gambit mesh updating, and Fluent flow solution modules within the Isight platform, enabling genetic algorithm optimization.

(2) The optimization platform is used to investigate the effect of different bump deformation locations on RAE2822 airfoil drag reduction, identifying the optimal deformation region. Results show 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 are obtained at different angles of attack. Drag reduction becomes more significant with increasing angle of attack: 6.15% at AOA = 2.31° and 10.28% at AOA = 2.8°.

(4) To maximize drag reduction without affecting lift characteristics, actively deformable adaptive bumps that can 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 demonstrate a maximum bump deformation of 4.4%, 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.