Effect of Subsonic Airfoil Leading Edge Shape on Boundary Layer Parameters Postprint

Authors: Xianjun Yu, Hongwei Zhu, Baojie Liu

Date: 2018-01-05T00:00:00+00:00

Abstract

The influence of circular-arc, elliptical, and curvature-continuous leading edges without suction peaks on blade profile boundary layer development was investigated using numerical simulation methods. By extracting blade surface boundary layer parameters under different operating conditions and combining them with changes in the blade surface boundary layer velocity profiles, it was found that the essential influence of the leading edge suction peak on blade profile performance lies in its effect on the initial development state of the boundary layer. An excessively strong diffusion parameter Dspike of the leading edge suction peak leads to deterioration of the boundary layer' s initial development state, causing premature transition and even separation bubbles, rapid thickening of the blade surface boundary layer, increased profile loss, and a reduced usable angle of attack range. The study also demonstrates that the designed curvature-continuous leading edge without suction peaks can always eliminate suction peaks near the leading edge on either the suction surface or pressure surface under any operating condition, thereby resulting in a superior initial state of the blade surface boundary layer compared to other leading edge profiles, and consequently better aerodynamic performance.

Full Text

Preamble

ChinaXiv Collaborative Journal ID: 162105

Effects of Leading-Edge Geometry on Boundary Layer Parameters in Subsonic Airfoils

Yu Xianjun, Zhu Hongwei, Liu Baojie
(National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, Collaborative Innovation Center for Advanced Aero-Engine, School of Energy and Power Engineering, Beihang University, Beijing 100191)

Abstract

This study employs numerical simulation to investigate the influence of circular, elliptical, and curvature-continuous spikeless leading-edge geometries on boundary layer development in subsonic compressor airfoils. By extracting boundary layer parameters across different operating conditions and analyzing velocity profile evolution, we reveal that the impact of leading-edge suction peaks on airfoil performance fundamentally stems from their effect on the initial development state of the boundary layer. An excessively strong leading-edge suction peak diffusion parameter Dspike deteriorates the initial boundary layer state, causing premature transition and even separation bubbles, rapid boundary layer thickening, increased profile losses, and reduced usable incidence range. The research also demonstrates that the designed curvature-continuous spikeless leading edge consistently eliminates suction peaks near the leading edge on either the suction or pressure surface under all operating conditions, thereby establishing a superior initial boundary layer state compared to other leading-edge geometries and consequently improving aerodynamic performance.

Keywords: Leading edge; Subsonic compressor blade; Boundary layer; Numerical analysis; Compressor

0 Introduction

Future aircraft propulsion systems demand compressors with significantly higher pressure ratios and efficiencies than current operational levels to improve thrust-to-weight ratios and reduce specific fuel consumption. Translating these requirements to blade design means achieving high loading, wide usable incidence ranges, and healthy blade surface boundary layers [1]. Research trends both domestically and internationally indicate that Controlled Diffusion Airfoils (CDA) represent a key technology for high-efficiency, high-loading compressor design, with extensive engineering applications in the subsonic environment of high-pressure compressor rear stages [2]. The core philosophy of CDA design involves controlling the distribution of isentropic Mach number or blade surface static pressure rise coefficient according to specific patterns to promote healthier boundary layer development and improve airfoil performance. In aero-engines, compressor blade leading-edge thickness is often extremely small, reaching approximately 0.2 mm or about 1% of chord length. Engineering design typically emphasizes structural strength considerations, and during airfoil design, the dramatic curvature changes at leading and trailing edges usually necessitate piecewise design—generating the blade body first, then adding the leading and trailing edges. This approach often results in large curvature discontinuities at the junctions between the leading edge and blade body. Furthermore, insufficient manufacturing precision and natural erosion or wear during service can alter the leading-edge geometry, with these geometric changes inevitably affecting blade performance.

As research on airfoils has deepened, numerous scholars have recognized that leading-edge geometry exerts a non-negligible influence on blade aerodynamic performance [3], making it a focal research topic. Traditional airfoils employ circular leading edges for manufacturing convenience; however, extensive numerical and experimental studies [4-7] have revealed that curvature discontinuities between circular leading edges and the blade body cause separation bubbles near the leading edge, leading to premature flow transition and increased losses. Lu Hongzhi et al. [4,5] conducted numerical simulations of elliptical leading edges, finding they significantly suppress suction peaks and improve aerodynamic performance. Based on the concept of controlling curvature transition between the leading edge and blade body, the authors proposed a circular leading edge with a flat platform, which improved blade surface flow and achieved results comparable to elliptical leading edges. Addressing leading-edge issues, Song Yin [8,9] and Yuan Chunxiang [10] proposed curvature-continuous design methods, demonstrating that such approaches better suppress leading-edge suction spikes and promote healthier boundary layer development, effectively improving blade performance. Experimental studies by Andrew P.S. Wheeler and Miller [11-12] on upstream rotor wake effects on profile losses showed that elliptical leading edges significantly reduce profile losses compared to circular leading edges under upstream wake interference. Goodhand and Miller [13] optimized elliptical leading edges to eliminate suction surface leading-edge suction peaks, achieving spikeless airfoil design at design conditions, and subsequently proposed that suction peak height has a critical value evaluable through the leading-edge suction peak diffusion factor Dspike—when exceeded, profile losses increase rapidly.

These findings indicate that leading-edge geometry substantially impacts airfoil performance, with different geometries producing varying effects under identical conditions. However, the mechanism by which leading-edge geometry influences blade surface boundary layer development remains incompletely understood. Therefore, this work focuses on a CDA airfoil, implementing circular, elliptical, and spikeless leading-edge designs without altering the blade body. Using numerical analysis capable of simulating boundary layer transition, we simulated the incidence-loss characteristics, extracted detailed evolution of blade surface boundary layers, and conducted in-depth parameter analysis. By comparing boundary layer development across different leading-edge geometries, we explore the mechanisms underlying leading-edge geometry effects on airfoil aerodynamic performance, providing essential theoretical support for further experimental research and airfoil optimization.

1 Methodology

1.1 Airfoil Parameters

The CDA airfoil parameters used in this study are listed in Table 1, with leading-edge geometries shown in [Figure 1: see original paper].

Table 1 CDA Airfoil Parameters

Parameter	Value
Chord (m)	
Solidity	
Inlet Mach number	
Stagger angle (°)	
Inlet metal angle (°)	
Camber angle (°)	
Turbulent intensity (%)	
Reynolds number (based on inlet velocity and chord)	5.45×10

1.2 Mesh Generation

Given the focus on boundary layer flow details, high mesh quality is essential. The mesh was generated using ICEM, employing O-grid topology around the blade surface to ensure good orthogonality while achieving local refinement. This approach guaranteed $y < 1$ on near-wall grids, with more than 10 mesh layers within the boundary layer and a growth ratio of 1.1 toward the mainstream region. The computational domain extends approximately 1.5 chord lengths upstream of the blade leading edge and 2 chord lengths downstream of the trailing edge. The spanwise direction contains 20 mesh layers, with a total model mesh count of 640,000.

1.3 Turbulence Model and Boundary Conditions

ANSYS CFX software was used for airfoil calculations. To accurately predict boundary layer transition and flow details, the Shear Stress Transport (SST) turbulence model with Gamma-Theta transition modeling was employed, using high-resolution schemes to ensure second-order accuracy. Boundary conditions were specified as: inlet boundary with total temperature, total pressure, and flow angle; outlet boundary with mass flow rate varying according to operating conditions; periodic boundary conditions in the pitchwise direction; symmetric boundary conditions in the spanwise direction; and smooth no-slip solid surface on the blade. Convergence was determined when residuals fell below 1.0×10 , with additional monitoring of mass, velocity, and pressure residual curves to ensure stable solutions.

1.4 Numerical Validation

Following mesh, numerical scheme, turbulence model, transition model, and boundary condition determination, experimental data was used to validate CFX results and confirm reliability. [Figure 3: see original paper] compares CFX predictions with cascade experimental results. Although three-dimensional flow effects exist in cascade experiments—with an axial velocity density ratio (AVDR) of approximately 1.02 due to endwall boundary layers—CFX calculations did not account for AVDR effects, causing slight deviations between computational and experimental results. However, overall agreement is good, particularly near the leading edge where suction peak simulation shows excellent consistency with experiments. While experiments did not exhibit separation bubble transition (possibly due to higher blade surface roughness and freestream turbulence), calculations revealed separation bubble transition near 40% chord location, creating a pressure plateau. Given that this analysis focuses on qualitative effects of the leading edge on blade surface boundary layers, the numerical simulation results provide reliable reference.

2 Effects of Leading-Edge Geometry on Airfoil Aerodynamic Performance

[Figure 4: see original paper] presents the computed total pressure loss characteristics for different leading-edge geometries. The minimum losses for all three geometries are essentially identical, but the usable incidence range (defined as the range where loss remains below twice the minimum loss) shows substantial differences. The circular leading-edge airfoil exhibits a usable incidence range approximately 2.5° narrower than elliptical and spikeless designs—equivalent to about 14.3% of the total operating range. The spikeless leading-edge airfoil demonstrates the widest usable incidence range and lowest losses, indicating that different leading-edge geometries create distinct blade surface boundary layer flow states, resulting in variations in loss and incidence range.

[Figure 5: see original paper] (flow deflection angle characteristics), [Figure 6: see original paper] (D-factor characteristics), and [Figure 7: see original paper] (deviation angle characteristics) reveal that the circular leading-edge airfoil' s pressure rise capability at high incidence is significantly inferior to the other two designs, with the elliptical leading edge performing moderately and the spikeless leading edge optimally. The circular leading-edge airfoil shows consistently higher deviation angles across the incidence range, with premature boundary layer separation at large positive and negative incidences causing loss to increase with incidence deviation. Conversely, the spikeless leading-edge airfoil exhibits the smallest deviation angles and latest boundary layer separation at extreme incidences, maintaining excellent flow conditions. In summary, with all other parameters held constant, leading-edge geometry alone produces substantial performance differences by altering blade surface boundary layer development states. To deeply investigate these effects, detailed comparative analysis of boundary layer development follows.

3 Boundary Layer Parameter Analysis

3.1 Boundary Layer Parameter Extraction Method

A custom boundary layer extraction program was developed. The computed flow field was first interpolated onto a grid strictly orthogonal to the airfoil surface, followed by boundary layer parameter extraction on this orthogonal grid. For any location, boundary layer thickness is calculated using:

$$= \quad 0(1 \quad 2\ )$$

where integration proceeds along the surface normal direction, with local density and velocity, and mainstream density and velocity. Mainstream identification relies on extremum points of the velocity gradient normal to the surface; when no extremum exists, a minimum gradient threshold is used. Since boundary layer parameters are insensitive to this threshold, the mainstream region' s gradient maximum can be appropriately increased as the criterion for distinguishing boundary layer from mainstream flow.

Momentum thickness is calculated using:

$$* = \quad 2\,(1 \quad 2\ )$$

Energy thickness is calculated using:

$$* = \quad 2\,(1 \quad 2\,2)$$

The shape factor is then derived from these parameters.

3.2 Boundary Layer Development at Different Incidence Conditions

[Figure 8: see original paper], [Figure 9: see original paper], and [Figure 10: see original paper] show boundary layer integral parameter variations on the suction surface at different incidences. At a large negative incidence of 35°, stagnation points for all three airfoils lie on the suction surface, with similar leading-edge flow processes around the suction side, resulting in essentially identical boundary layer development. Transition occurs at 60% chord, causing rapid boundary layer thickening and increased friction losses, yielding consistent suction surface losses.

At the design incidence of 47°, stagnation points reside near the leading edge. The spikeless airfoil exhibits the smallest leading-edge curvature variation, followed by the elliptical airfoil. Both have similar suction-side leading-edge flow processes without strong sudden compression/expansion, undergoing transition at 40% chord with subsequent rapid thickening and friction loss increase. However, the circular airfoil' s curvature discontinuity creates intense sudden compression and over-expansion—i.e., a strong leading-edge spike—generating a separation bubble near the leading edge and causing separation bubble transition on the suction surface. This results in the thickest boundary layer and highest suction surface loss, while elliptical and spikeless airfoils show minimal and essentially identical losses.

At a large positive incidence of 50°, stagnation points shift to the pressure surface, requiring flow to travel around the leading edge to the suction surface. The three airfoils' differing curvature variations create varying degrees of compression and expansion. The circular airfoil maintains maximum curvature (except at the leading-edge point) but exhibits curvature discontinuity at the leading-edge/blade-body junction, producing the strongest sudden compression/over-expansion and most intense leading-edge spike, with a separation bubble on the suction surface. Transition moves forward to the leading edge, causing rapid boundary layer thickening and large trailing-edge separation, increasing suction surface losses. The elliptical airfoil has large curvature at the leading-edge point but smaller curvature elsewhere, with reduced curvature discontinuity at the junction, resulting in weaker compression/expansion. Although transition also occurs near the leading edge, boundary layer thickening is slower, yielding smaller loss increases than the circular design. The spikeless airfoil, despite maximum curvature at the leading-edge point, has minimum curvature elsewhere with continuous curvature, significantly weakening the expansion process and optimizing leading-edge flow. Transition remains at 30% chord—later than the other designs—with the weakest trailing-edge separation and smallest losses.

[Figure 11: see original paper], [Figure 12: see original paper], and [Figure 13: see original paper] show pressure surface boundary layer integral parameter variations. At 35° incidence (large negative), stagnation points on the suction surface create pressure surface flow processes similar to the suction surface at large positive incidence. While pressure surface transition occurs at the leading edge (separation bubble transition) for all designs, the circular airfoil's strongest compression/expansion causes the fastest boundary layer thickening and greatest thickness, followed by the elliptical design, with the spikeless airfoil showing the thinnest boundary layer. Consequently, the circular airfoil exhibits the highest pressure surface loss, elliptical is intermediate, and spikeless is minimal.

At the 47° design incidence, stagnation points near the leading edge create strong compression/expansion on the suction surface and correspondingly weaker processes on the pressure surface. No leading-edge pressure surface transition occurs (shape factor around 2.5), maintaining a fully laminar pressure surface state with minimal overall losses. However, elliptical and circular airfoils exhibit local disturbances near the leading edge due to curvature discontinuities, creating friction coefficient spikes without triggering typical laminar separation. These differing disturbances alter initial boundary layer development states, producing different development characteristics from leading edge to trailing edge, though losses remain similar. At 50° incidence, further weakened compression/expansion on the pressure surface maintains laminar flow, similar to the 47° condition.

[Figure 14: see original paper] shows boundary layer velocity profiles at different streamwise positions. At 50° incidence, the circular airfoil exhibits the most severe leading-edge acceleration and expansion, with velocity profiles transitioning from fullest to most deficit-dominated near the wall between X=0.0005 and X=0.0024. A separation bubble initiates before X=0.0009 and ends after X=0.0024, evidenced by a Cf drop to zero in [Figure 10: see original paper]. By X=0.0075, the bubble has reattached, but velocity profile fullness remains inferior to other designs. Shape factor distributions in [Figure 8: see original paper] indicate post-bubble transition, causing rapid boundary layer thickening significantly exceeding other designs.

The spikeless airfoil shows no separation characteristics near the leading edge, consistent with [Figure 10: see original paper]. From X=0.0009 onward, its suction surface velocity profiles are the fullest with minimal boundary layer thickness. At 50° incidence, Cf approaches zero between 20-30% chord, indicating near-separation conditions where transition occurs (as shown in [Figure 8: see original paper]), with the transition location between X=0.036 and 0.054. At X=0.022, the spikeless airfoil exhibits a typical laminar velocity profile with smaller near-wall velocity gradients than other designs, while at X=0.06 it has transitioned to a typical turbulent profile through a relatively small-scale separation bubble. The later transition location produces a healthier subsequent turbulent boundary layer.

The elliptical airfoil shows separation bubble scales comparable to but slightly weaker than the circular design, with complete transition after the bubble, resulting in a laminar boundary layer on the suction surface. This aligns with results in [Figure 8: see original paper] and [Figure 10: see original paper]. Overall, the elliptical airfoil’ s boundary layer thickness and fullness fall between circular and spikeless designs.

In summary, even under identical adverse pressure gradients, different leading-edge geometries create distinct leading-edge flow processes that directly affect initial boundary layer development states, producing significant differences in blade surface flow conditions and energy deficits (as shown in [Figure 9: see original paper] and [Figure 12: see original paper]), i.e., different profile losses. This explains why different leading-edge shapes cause substantial variations in both profile loss and usable incidence range. The impact of leading-edge geometry is intimately related to leading-edge flow intensity—stronger local acceleration and deceleration generally produce greater flow losses.

4 Relationship Between Leading-Edge Spike and Boundary Layer Parameters

4.1 Effects of Different Leading-Edge Geometries on Spike Development

To analyze key factors in local leading-edge flow disturbances, the Dspike parameter proposed by Goodhand and Miller [13] warrants examination. The parameter is defined as:

$$=$$

where variables are defined in [Figure 15: see original paper]. This parameter, derived from the D-factor concept, characterizes the intensity of sudden compression at the leading edge.

[Figure 16: see original paper] shows the local static pressure coefficient near the leading edge versus incidence for different geometries. Combined with [Figure 17: see original paper] showing suction surface Dspike variation, Dspike increases with incidence, intensifying the leading-edge suction peak. Different geometries exhibit varying Dspike growth rates: circular leading edge increases fastest, most readily forming suction surface separation bubbles and increasing losses. The spikeless design maintains low Dspike at negative incidences with slow growth, accelerating only beyond 45° incidence. The elliptical design falls between these extremes. [Figure 18: see original paper] reveals that pressure surface leading-edge spikes are smaller, with Dspike decreasing as incidence increases, reducing their performance impact. The spikeless design achieves spikeless flow on the suction surface from minimum-loss incidence (around 45°) through all negative incidences, and on the pressure surface from minimum-loss incidence to positive incidence limits. The circular leading edge shows strong spikes across all conditions except at extreme negative (suction surface) and positive (pressure surface) incidences. The elliptical design achieves spikeless flow on the suction surface near negative incidence limits and on the pressure surface at maximum positive incidence, with spikes present under other conditions. Clearly, spike intensity directly correlates with boundary layer development and profile loss. The spikeless airfoil’ s superior performance stems from essentially eliminating or significantly weakening spikes across a broad operating range, necessitating deeper analysis of the relationship between boundary layer parameters and spikes.

4.2 Relationship Between Leading-Edge Spike and Boundary Layer Parameters

Based on the above analysis, boundary layer momentum thickness and shape factor at 10% chord were extracted to examine relationships with Dspike. [Figure 19: see original paper] and [Figure 20: see original paper] show that energy loss thickness increases with Dspike, with rapid loss increase after separation bubble onset. For suction surface results in [Figure 19: see original paper], spikeless and elliptical airfoils show greater energy loss thickness than circular designs at identical Dspike values. Significant suction surface loss increase occurs only when Dspike > 0.17 (critical values near 0.2 for spikeless and circular designs), substantially deviating from Goodhand and Miller’ s [13] Dspike $>$ 0.1 criterion. Pressure surface results in [Figure 20: see original paper] show similar relationships across designs, with circular airfoils causing slightly smaller losses at identical Dspike. Significant pressure surface loss increase occurs when Dspike > 0.12 (circular design critical value near 0.14), closer to the Goodhand and Miller criterion, though the circular design’ s critical value approaches 0.18. Thus, circular leading-edge airfoils exhibit higher Dspike tolerance from a loss perspective.

[Figure 21: see original paper] and [Figure 22: see original paper] present correlations between shape factor and Dspike in the leading-edge region. On the suction surface, shape factor decreases rapidly when Dspike > 0.17, indicating transition from laminar to turbulent state through separation bubble formation. In the laminar regime, circular leading-edge airfoils show smaller shape factors (lower near-wall velocity gradients), explaining their smaller energy loss thickness, likely related to local leading-edge curvature. Pressure surface results in [Figure 22: see original paper] show transition onset at Dspike 0.12 (circular design critical value near 0.14). The rapid shape factor decrease followed by increase suggests that excessive Dspike (spikeless and elliptical > 0.13, circular > 0.15) may directly cause large-scale negative-incidence pressure surface separation, rapidly increasing losses.

5 Conclusions

This study investigated the mechanisms by which different leading-edge geometries affect blade surface boundary layer development through numerical simulation of three airfoil designs. The main conclusions are:

1. Different leading-edge geometries create varying leading-edge flow processes (i.e., different leading-edge spikes). Excessively strong spikes degrade airfoil performance and reduce usable incidence range. The circular leading edge exhibits the most dramatic flow variations, larger losses, and narrower incidence range, while the spikeless design weakens spikes, reduces losses, and expands the usable incidence range.
2. The primary impact of leading-edge spikes on performance lies in their influence on the initial boundary layer development state. Overly strong spikes produce less-full velocity profiles, making the boundary layer less resistant to adverse pressure gradients, causing premature transition and separation bubbles, rapid thickening, increased losses, and reduced incidence range.
3. Suction surface Dspike increases with incidence, degrading suction surface performance, while pressure surface Dspike exhibits the opposite trend.
4. Profile losses increase with Dspike, with abrupt performance deterioration beyond critical values.
5. The designed spikeless leading edge consistently eliminates suction peaks near the leading edge on either suction or pressure surface under all conditions, establishing a superior initial boundary layer state compared to other geometries.

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