Effect of Camber on Non-axisymmetric End-wall Contouring Performance in Compressor Linear Cascades

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Abstract. In order to explore non-axisymmetric end-wall’s mechanism of secondary flow control in compressor cascade, based on three-dimensional numerical calculation, this paper analysed effects of camber on non-axisymmetric end-wall contouring performance in compressor linear cascades. Results showed that non-axisymmetric end-wall reduces the corner separation loss mainly by suppressing the interaction between the crossflow and the suction surface boundary layer and decreasing the adverse pressure gradient on suction surface. Meanwhile, non-axisymmetric end-wall partly enhances the cross flow, increasing the secondary flow loss. At the incidence of 0°, the increase of the secondary flow loss caused by the non-axisymmetric end-wall plays the leading role when the camber angle is 20°; with the increase of camber angle, the reduction of corner separation loss becomes the leading role. At the incidence of 7°, the hub-corner stall is removed by the non-axisymmetric end-wall when the camber angle increases to 40°, decreasing the loss remarkably.

1. Introduction

The compressor is one of the core components in gas turbine engines. The aerodynamic design of the compressor is developing towards high load, high efficiency and high surge margin, which will cause the secondary flow problem inside the compressor to become serious and the risk of corner separation to increase. The secondary flow loss becomes a more significant part of total loss in blade passage since the trailing edge separation near mid span of the blade can be avoided by modern blade design techniques. The corner separation is one of the most important problems in secondary flow control, it not only causes the high loss in corner region, but also worsens the inlet conditions of downstream and then makes the problem of corner separation more serious at downstream.

According to concepts of Horlock et al. [1] and Cumpsty [2], the corner separation in compressor is not only related to the reverse flow of boundary layer fluids under the adverse pressure gradient (APG), but also affected by various secondary flows in the near end-wall region. The crossflow is the main factor inducing the corner separation. Due to the serious harm of corner separation, method for corner separation control has always been a very important research subject.

Because of its significant influence on the secondary flow control in turbine and the feature that no change in blade geometry is required, the technology of non-axisymmetric end-wall contouring has
already become an important research object in the field of flow control. And it has been proved also effective for the secondary flow control in compressor in recent years.

The technology of non-axisymmetric end-wall contouring was first developed in turbines. Rose [3] first successfully developed the concept of non-axisymmetric end-wall contouring and the principle of controlling static pressure distribution through streamline curvature. In fact, the main secondary flow problems in turbine and compressor are different, and the applications of non-axisymmetric end-wall contouring for turbine and compressor are also different. For compressor, one of the main usages of non-axisymmetric end-wall contouring is the corner separation control.

Preventing the interaction between the crossflow and the suction surface boundary layer is one of the main methods to control the corner separation. Harvey [4] compared the performance of several non-axisymmetric end-wall structures in linear cascades. It was found that non-axisymmetric end-walls in the research have a significant influence on crossflow and can restrain the corner stall. Dorfner et al. [5] proposed a new non-axisymmetric end-wall that generates vortex through an end-wall separation boundary line and a groove near suction surface to weaken the interaction between the crossflow and the suction surface boundary layer. Later, another non-axisymmetric end-wall was developed in cascades with fillet by Reuter et al. [6]. Identically, it reduces the loss by weakening the interaction between the crossflow and the suction surface boundary layer. Besides, JIN et al. [7, 8] applied the artificial neural network (ANN) and adaptive genetic algorithm (AGA) [9, 10, 11, and 12] to the non-axisymmetric end-wall optimization design.

Although the positive effect of the technology of non-axisymmetric end-wall contouring in the compressor has been preliminarily confirmed, there are still many topics to be further studied. This paper explored the non-axisymmetric end-wall’s mechanism of secondary flow control in compressor cascade by comparing effects of non-axisymmetric end-wall on end-wall region’s flow in cascades with different camber angles.

2. Compressor cascades and numerical approach

2.1. Compressor blade geometry

Cascades with different camber angles were generated based on a controlled diffusion airfoil (CDA062). These cascades were generated without any 3D blading techniques, without tip gap and fillet. Table 1 gives some cascade parameters and CFD conditions.

| Parameters            | Values          |
|-----------------------|-----------------|
| Camber angle/°        | 20, 30, 40      |
| Solidity              | 1.52            |
| Stagger angle/°       | 30              |
| Blade chord/mm        | 50              |
| Aspect ratio          | 2.4             |
| Inlet metal angle/°   | 40, 45, 50      |
| Inlet Mach number     | 0.15            |

2.2. Non-axisymmetric contoured end-wall

Non-axisymmetric end-walls used in the present research were generated based on the non-axisymmetric end-wall optimized by ZHAO et al. [7]. The references [9, 10, 11, 12] give a detailed description for the optimization method. As shown in Fig. 1, the end-walls were defined by two straight lines and four B-Splines. Three relative Cartesian coordinates of the B-spline control points were kept the same as the non-axisymmetric end-wall optimized by ZHAO et al. [7] to generate non-axisymmetric end-walls for different camber angles. The leading edge was set to be the datum point for the relative
Cartesian coordinates. Figure 2 shows the contoured end-wall’s (CEW) contour height relative to the flat end-wall (FEW) for cascades with different camber angles.

![Figure 1. Non-axisymmetric end-wall parameterization](image1)

![Figure 2. CEW contour height relative to FEW for cascades under different camber angles](image2)

2.3. **Numerical approach**

The grid generation tool of NUMECATM/IGG software package was used to generate computational meshes. The numerical computations were executed by the CFX software. Turbulence model used for the computational domain is the shear stress transport (SST) model based on k-ω. Because of the relative low Reynolds number (about 180000), the γ-Reθ transition model was introduced to predict the transition process. The y+ values on most regions of the blade and end-wall were controlled below or close to unity. The grid scheme was determined by the grid independence validation. The total number of grid nodes is about 2.6 million.

For boundary conditions of the numerical computation, the total pressure and total temperature at the inlet boundary were set to be 101325Pa and 288.15K at standard day. The flow direction was given at the inlet boundary to specify the incidence. The averaged static pressure at the outlet boundary was adjusted to get an averaged inlet Mach number of 0.15. The periodic boundaries were set to be translation periodicity boundary conditions. The solid surfaces were defined as adiabatic boundaries.

3. **Results and discussion**

Performances of the contoured end-walls in cascades with different camber angles were investigated at two operating points including 0° incidence and 7° incidence. The main criterion for contoured end-wall performance is the total pressure loss coefficient. In addition, the static pressure coefficient distribution and near wall streamlines on blade surface are used to analyze the situations of corner separation. The
The definition of total pressure loss coefficient and static pressure coefficient are shown in Eq. (1) and Eq. (2):

\[ \omega = \frac{p_1^* - p_2^*}{p_1^* - p_1} \]  

\[ C_p = \frac{p^* - p_1}{p_1^* - p_1} \]

Where \( p_1^* \) and \( p_1 \) are the total pressure and the static pressure of inlet plane, \( p_2^* \) is the total pressure of outlet plane. The inlet plane is located at 100% axial chord upstream of the leading edge. The outlet plane is located at 100% axial chord downstream of the trailing edge.

3.1. Results at 0\(^\circ\) incidence

Figure 3 shows the span-wise distributions of mass flow averaged total pressure loss coefficient. Loss near 2\% span in CEW cascades is slightly higher than FEW cascades. The performance of CEW in loss reduction improves as the camber angle increases. For cascades of CA20, there is only slight loss improvement near 8\% span. For cascades of CA40, the loss from 5\% to 15\% span is decreased remarkably by CEW.

![Figure 3](image-url)
Figure 4. Limiting streamlines on suction surface and end-wall at 0° incidence

Figure 4 shows limiting streamlines on both suction surfaces (SS) and end-walls. In FEW cascades, the cross flow near suction surface flows upstream under the effect of the adverse pressure gradient (APG), generating the separation lines of reverse flow at corner region. The reverse flow on suction surface appears under the effect of the reverse flow at corner region. As the camber angle increases, the cross flow gets enhanced, thus more boundary layer fluids gather at the corner region, making the corner separation on suction surface to expand.

In CEW cascades, the direction of the separation lines on end-walls is the opposite of FEW cascades. This indicates that the reverse flow at corner region is replaced by stream-wise vortex. The stream-wise vortex weakens the interaction between the crossflow and the suction surface boundary layer. Thus, the reverse flow on suction surface is suppressed. Besides, that the cross flow on end-walls are partly enhanced should be responsible for the loss increase near 2% span.
Figure 5. Pitch-wise distributions of static pressure coefficient at the position of 70% axial chord

Figure 6. Comparison of flow structures at corner region

The changes of flow structures originate from the changes of pressure fields caused by CEWs. Figure 5 shows the pitch-wise distributions of static pressure coefficient in CA30 cascades at the position of 70% axial chord. Figure 6 shows the comparison of flow structures at corner regions in CA30 cascades. The CEW induces a steeper cross-passage pressure gradient (CPG) at the region of 0.7 to 0.9 relative pitch, thus the cross flow on end-walls are partly enhanced. Besides, as shown in Figure 6, a pressure rise near suction surface caused by CEW makes fluids at corner region flow away from suction surface, making the reverse flow at corner region to be replaced by stream-wise vortex.

Figure 7. Distributions of static pressure coefficient on blades at 0° incidence

Figure 7 shows the distributions of static pressure coefficient on blades. It can be seen that the adverse pressure gradients (APG) in FEW cascades are reduced by CEW. The reduced adverse pressure gradients can let the development of the suction surface boundary layer slow down. This is of benefit for weakening the reverse flow on suction surface.
3.2. Results at 7° incidence

Figure 8 shows the span-wise distributions of mass flow averaged total pressure loss coefficient. For cascades of CA20 and CA30, the loss under 10% span is decreased by CEW. The performance of CEW in loss reduction improves as the camber angle increases. However, the loss from 10% to 25% span is increased by CEW. For cascades of CA40, there is a large region of high loss in FEW cascade which indicates the existence of the hub-corner stall [13]. The CEW causes the loss under 30% span to decrease significantly.

Figure 8. Span-wise distributions of total pressure loss coefficient at 7° incidence

Figure 9. Limiting streamlines on suction surface and end-wall at 7° incidence
Figure 9 shows limiting streamlines on both suction surfaces (SS) and end-walls. For cascades of CA20 and CA30, CEW suppresses the corner separation by weakening the interaction between the crossflow and the suction surface boundary layer. Meanwhile, the enhanced cross flow induces span-wise migration on suction surface, thus the loss from 10% to 25% span is increased by CEW. For cascades of CA40, reverse flow appears on both suction surface and end-wall in FEW cascade which indicates the existence of the hub-corner stall [13]. The reverse flow on end-wall is removed by CEW, thus the loss under 30% span decreases significantly.

3.3. The effect of camber angle on non-axisymmetric end-wall’s performance

Figure 10 shows the effect of camber angle on non-axisymmetric end-wall’s performance. It can be seen that the performance of CEW in loss reduction improves as the camber angle increases at both 0° incidence and 7° incidence. For cascades of CA20, the total pressure loss coefficients in CEW cascades are slightly higher than FEW cascades at both 0° incidence and 7° incidence. The CEW can effectively reduce the loss under other conditions. Especially for cascade of CA40 at 7° incidence, the loss is reduced significantly.

It can be inferred from the analysis above that CEW reduces the corner separation loss mainly by suppressing the interaction between the crossflow and the suction surface boundary layer and decreasing the adverse pressure gradient on suction surface. Meanwhile, CEW partly enhances the cross flow, increasing the secondary flow loss. The increase of the secondary flow loss caused by the CEW plays the leading role when the camber angle is 20°. With the increase of camber angle, the reduction of corner separation loss becomes the leading role.

![Figure 10. The effect of camber angle on non-axisymmetric end-wall’s performance](image)

4. Conclusion

This paper explored the non-axisymmetric end-wall’s mechanism of secondary flow control in compressor cascade by comparing effects of non-axisymmetric end-wall on end-wall region’s flow in cascades with different camber angles. Results show that the non-axisymmetric end-wall in this paper reduces the corner separation loss mainly by suppressing the interaction between the crossflow and the suction surface boundary layer and decreasing the adverse pressure gradient on suction surface. Meanwhile, the non-axisymmetric end-wall partly enhances the cross flow, increasing the secondary flow loss.

The increase of the secondary flow loss caused by the non-axisymmetric end-wall plays the leading role when the camber angle is 20°. With the increase of camber angle, the reduction of corner separation loss becomes the leading role. Thus, the performance of non-axisymmetric end-wall in loss reduction improves as the camber angle increases.
At the incidence of 7°, the hub-corner stall is removed by the non-axisymmetric end-wall when the camber angle increases to 40°, decreasing the loss remarkably.

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