CONTROL OF SECONDARY CROSSFLOW IN A HIGH-SPEED COMPRESSOR CASCADE BY ENDWALL FENCES WITH VARYING LOCATIONS

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ABSTRACT

It is well known that the secondary flow, including vortices, boundary layer, and three-dimensional separation, is detrimental to the efficiency and stability in the axial compressor. As a passive secondary flow control technique, the endwall fence is considered to overcome the adverse pressure gradient by blocking the crossflow. On this paper, a steady computational study is carried out in a high-speed compressor cascade. Two categories of fence configurations, i.e., embedded in the front and the back of flow passage, have been investigated. For each category, the fence position is selected at 7 locations ranging from 20% to 80% pitch length away from the blade pressure surface, the interval between each case is 10% pitch length. In the comparison between the datum and the fenced cascade, the case of 50% pitch length away from the blade suction surface in the category of front fences is most effective in the improvement of the aerodynamic performance. At the design point, this case decreases the loss coefficient and the blockage coefficient by 6.3% and 6.5%, respectively. Meanwhile, it increases the absolute value of the flow turning angle by 0.9%. From the perspective of the vortex structure, both optimum fences in the front and back category can suppress the passage vortex by inducing the counter-rotating fence vortex, of which scale has a relationship with the contact area between fence surface and the crossflow. Last but not least, the fenced cascade with an optimum performance both in loss mechanism and vortex structure has been investigated under varying inlet incidences. The comparison analysis of the baseline and optimum fence and demonstrates that there is a reduction of the loss exists at negative incidences while an augment occurs at positive incidences. In summary, the optimum case of endwall fence can effectively weaken the endwall loss and thereby enlarge the cascade operating range under negative incidences.

INTRODUCTION

The efficiency is probably the most crucial index for most turbomachines, which is influenced by some complex factors, such as profile loss, tip leakage loss, and endwall crossflow (Denton 1993). Over the past few decades, enormous efforts have been taken to reduce the endwall loss of different types of compressors. For modern high-speed compressors, both the higher transverse pressure gradient and the viscous effect may inevitably increase endwall loss, which carries the challenges to obtain further aerodynamic improvements (Gbadebo, Cumpsty, and Hynes 2005). Hence the endwall loss has a strong influence on overall cascade loss.

The flow control technology, acting on a small scale, is used to bring the desired behaviour change into a larger flow (Gad-el-Hak 1996). It is proved that flow control is effective in the sources of endwall flow such as the boundary separation, skin-friction, low momentum, and wake mixing. The mainly two types of flow control, active and passive, are witnessing the interest of market and research (Hecklau et al. 2012). This kind of classification for flow control methods considers the energy involved and the control loop included. Active control such as boundary layer suction (Zhang et al. 2018), synthetic jet (Zander et al. 2011), and plasma actuation (Li et al. 2010), is widely researched depends on the recent advancement of computers and experiments. However, passive control is simpler to apply to an existing device and bring lower cost due to its simpler form.

Passive flow control of endwall loss is currently employed via shaping: endwall fence/groove (Hage and Paschereit 2007), vortex generator (Dias et al. 2015), endwall contouring (Chen et al. 2012), casing treatment, etc, which is beneficial to delay or provoke separation. As a structural bulge along streamwise on endwall surface, endwall fence is available to hinder the crossflow and

generate the fence vortex (Liu et al. 2017). In fact, the initiate of crossflow separation is induced as well as the mixing is enhanced under the positive effect of endwall fence. Yet, the negative characteristic is higher losses and thicker boundary layer in near-fence region.

Endwall fence technique has been utilized to reduce secondary flow loss in turbine cascades for a long history. Experimental investigations of (Kawai 1994) and Govardhan and Kumar (2011) found that fence with 1/3 height of the inlet boundary layer thickness when located half a pitch away from the blade suction side is optimal. Moreover, (Moon and Koh 2001) have simulated the complicated vortex structure of flow field in turbine cascade with and without endwall fence, which leads to an understanding on the formation of counter-rotating streamwise fence vortex and explains the mechanism of controlling secondary flow development. Based on these findings in the turbine, For loss reduction in a low-speed compressor, (Zhong et al. 2009) utilized experimental and numerical methods to investigate on the effect of the single streamwise endwall fence with various geometry parameters and pitchwise positions. He found that the optimal fence, 1/3 height of boundary and 75% length of the chord, can reduce 22% of cascade total pressure loss when is located on 30% pitch away from the blade pressure surface. Move to the high-speed compressor, (Hergt et al. 2011) developed a series of non-axisymmetric endwall modification strategy, including a row of endwall fences with various heights. This strategy not only reduced the total loss of the cascade obviously in the aerodynamic design, but also showed the mechanism of endwall loss.

This article firstly focuses on the dependency of aerodynamic performance on the location of a single streamwise endwall fence under the design point, where the steady numerical study is conducted by means of Reynolds-Averaged Navier-Stokes approach. Then the detail of the flow field is discussed in order to understand the mechanism of flow control under a single streamwise endwall fence. The last but not the least, the comparison between the loss curve of the datum and the critical fenced cascades gives an indication on the further research.

METHODOLOGY

Configurations of cascade

The baseline linear configuration is a highly loaded compressor cascade with a NACA65-K48 profile (see Figure 1). The main geometrical and aerodynamic parameters of the cascade, as well as the test conditions in the aerodynamic design point, are shown in Table 1.

The commercial flow solver ANSYS CFX is utilized to solve the steady RANS equations to analyse flow phenomena in the endwall region in detail, the γ - θ transition model is employed in conjunction with the SST turbulence model, under $Ma=0.7$. For all cases, a fine multi-block grid with an H-O-H topology, as shown in Figure 2, is densified to sufficiently resolve the blade and endwall boundary layer. The value of y^+ adjacent to the wall is approximately 1.0, in

order to meet the requirements of low Reynolds turbulence model.

Table 1 Main geometric parameters of profile

Parameter	symbol	Value	Unit
Chord length	C	60	mm
Span	H	100	mm
Pitch	T	33	mm
Inlet geometry angle	α	48	°
Inflow Mach number	Ma_{in}	0.7	-
Inflow boundary layer thickness	δ	13	mm

Figure 1 Diagram of the Cascade Geometry

Numerical approach and validation with experiment

Figure 2 Typical mesh

Figure 3 grid independence study

Numerical simulations are conducted with the same geometry and boundary conditions as those in the experimental condition. At the inlet, total pressure, total temperature (310K), and flow angle (-6°) are obtained from validation experiments. At the outlet, the static pressure is specified. At the blade surface and hub, no-slip and adiabatic wall conditions are used. To reduce simulation cost, a single passage is cut down to a half span. Hence the top surface of

computational domain is set to be a symmetric boundary, and both its sides set to be periodic boundary conditions.

The results of grid independence study are shown in Figure 3, where the grid of datum cascade consists of nearly 1.1 million nodes, and that of fenced cascade contains totally about 1.5 million nodes.

Figure 4 Validation of Computational Results:(a) Contours of the Total Pressure Loss; (b) Mass-average total pressure coefficient; (c) Numerical Limiting Streamlines and Experimental Oil Flow Visualization

Figure 5 Distribution of Three-dimensional Computational Grid

Figure 4(a) shows the contours of total pressure loss at the exit of the cascade, i.e., 60%C downstream the blade TE. Corresponding experimental results are obtained from a high-speed linear cascade wind tunnel of Dalian Maritime University. Although the calculated value is lower than experimental results in Figure 4(a) and 4(b), the distribution and tendency of C_{pt} is basically consistent. Moreover, Figure 4(c) shows the oil-flow visualization and the corresponding numerical limiting streamlines on the suction surface at 0°

incidence condition. In both simulation and experiment, the separation bubble exits at the 30%C, and the corner separation in the rear part of the blade is obviously well-matched. These results illustrate that the calculated results have a good consistency with the experimental results both in aspects of quality and quantity.

Figure 5 presents the computational grid used in this study, the sculpt of fence is based on the rectangular sheet with rounding LE as well as TE, and parallel to the blade camber line. In order to explore the correlation between the endwall location of fence devices and the aerodynamic performance of cascades, fences in 14 cases with the same geometrical parameters (5mm in width, 75%C in length and 10% inlet boundary thickness in height) are divided into two categories: FF and BF (see Figure 1). Table 2 details fenced locations, which is selected at 7 locations ranging from 20% to 80% pitch length away from the blade pressure surface. The interval between two adjacent fences is 10% pitch length.

Table 2 Main geometric parameters of profile

Categories	Distance from the SS (%T)						
FF cases	20	30	40	50	60	70	80
BF cases	20	30	40	50	60	70	80

Calculation formulae

The parameters used to quantificationally evaluate the aerodynamic performance of cascade are denoted as followed:

- (1) Total pressure coefficient:

$$C_{pt} = \frac{P_{t,in} - P_{t,out}}{P_{t,in} - P_{in}} \quad (1)$$

- (2) The total flow blockage coefficient in the passage:

$$B = \frac{A_b}{A_{out}} = \frac{\iint (1 - \frac{\rho V_z}{\rho_e V_e}) dA}{A_{out}} \quad (2)$$

- (3) The pitch-averaged value of total pressure loss coefficient:

$$\overline{C_{pt}} = \frac{\int C_{pt} dt}{dt} = \sum_{i=1}^n (C_{pt_i} \Delta t_i) / t \quad (3)$$

- (4) Axial vorticity:

$$\Omega = \frac{\partial V_x}{\partial y} - \frac{\partial V_y}{\partial x} \quad (4)$$

- (5) The static pressure coefficient:

$$C_p = \frac{P_{out} - P_{in}}{P_{t,in} - P_{in}} \quad (5)$$

- (6) The secondary flow in Cartesian coordinates of the linear cascade:

$$v_s = V \times \cos \beta \times \sin(\alpha_s) \quad (6)$$

$$\omega_s = V \times \sin \beta \quad (7)$$

RESULTS AND DISCUSSION

Variations in aerodynamic performances of cascades

Figure 6 shows the variations of three categories of cascades (the datum, FF, and BF) on general aerodynamic performance versus seven crosswise distances(t), under the design point. On the whole, both the 50% cases of FF and BF are capable of reducing the total pressure loss and blockage coefficient at the same time. Furthermore, the mid-case of FF can mostly lower the outlet flow turning angle.

As shown in Figure 6(a) and 6(b), the total pressure loss and blockage coefficient shows a concave, which means the fences located medially have a positive effect on this cascade. In Figure 6(c), both the curves of turning angle in the series of FF and BF are fluctuating with the increasing distance between FSS and PS. Among the FF cases, the aerodynamic performance of 20%-50% cases is better, especially 40% and 50% cases: C_{pt} is singly reduced by 5.9% and 6.3%; the B decreased 11.5% and 6.5%; the β slightly dropped 0.2% and 0.9%. However, none of the BF cases can lower the three primary performance simultaneously. Only the 50% case declines the C_{pt} and B by 0.5% and 4.4%.

Figure 6 Influence of Endwall Fence Locations on Main Aerodynamic Parameters

Figure 7 Distribution of Static Pressure Coefficient at Different Blade Heights

The values of C_p , distributed at 10% and 40% height on the blade surface of FF and EF cascades respectively, is shown in Figure 7. The enclosing area of C_p curve represents the blade loading. In general, the fence configurations do not affect the blade loading in midspan(40%H) but can largely change that near the endwall. The concave at midspan of the datum cascade respects the suction surface separation bubble (shown by the pointers in Figure 7(a) and 7(b)). Compared to the Ori, the case of the 50% less the pressure gradient and flattens the concave of the separation bubble. In the endwall region, the static pressure of 50% FF on SS keeps lower until 70% C , which is nearly as long as the fence configuration, then raises up more quickly than the Ori. As a result, the blade load at 10%H becomes higher in the front but lower near TE. The case of 20% T plays less effect on the distribution of C_p on SS.

In Figure 8, the developments of loss distribution are depicted on several traverse planes, which are vertical to the axial direction and located at 10% C , 30% C , 50% C , 70% C , 90% C , 110% C , 135% C , and 160% C downstream of the leading edge, respectively. As seen in Figure 8(a), there are three high loss regions (encircled by the iso-line) located according to the endwall boundary layer/CV, PV and corner separation/CSV, respectively. Compared to the datum cascade, a new loss region appears near the FSS, which enlarges the endwall boundary layer loss. That because the block effect, played by fence configurations on the endwall crossflow, leads to the momentum wastage of the endwall crossflow. The difference between the FF and BF is: the wake of a fence in FF has longer distance from the outlet in order to dissipate by interacting more with the endwall crossflow. That is obviously shown in 20% and 50% cases (in Figure 8 (b), (c), (d), and (e)), the wake of BF still occurs on the outlet plane. However, it is hard to distinguish the fence wake from the corner separation loss in 80% cases. For

another remarkable change out of passages of fenced cascades, the high loss regions of PV and corner separation/CSV gather together to change the entire shape of loss.

Figure 8 Loss Coefficient Contours at Different Axial Sections

(a) Cases of FF

(b) Cases of BF

Figure 9 Spanwise Distribution of Pitchwise Mass-averaged Total Pressure Loss Coefficient at Cascade Exit

(a) Cases of FF

(b) Cases of BF

Figure 10 Spanwise Distribution of Pitchwise Mass-averaged Flow Angle at Cascade Exit

The distribution of massflow-average C_{pt} along with blade height in Figure 9(a) shows that 50%T FF can

simultaneously reduce the loss of the corner separation (between 14%H~24%H) and largely decrease the loss of endwall boundary layer (above 6%H). For this reason, the uniformity along spanwise at cascade exit is raised, which brings a more homogeneous inflow condition to the next cascade. In BF cases, the 50%T and 80%T fence configurations also effectively decrease the mixing of boundary layer and corner separation (above 6%H), but their higher additional loss increases the loss distributed in 5%H~10%H. In addition, both of the optimized fence cases in the series of FF and BF can the largest extent reduce the value gradient along with the blade height.

The selected cases of FF and BF show the optimal effect of the mass-average outflow angle in Figure 10. Due to the blockage effect fence configurations bringing to the endwall crossflow, the flow angle near the endwall (0%H~6%H) is improved by the cases of 20%T FF, 50%T FF, 50%T BF, and 80%T BF. Reversely, both of the 20%T cases in FF and BF have less effect on changing the distribution curves of the Ori. Among 8%H~18%H, 80%T cases in FF and BF play an opposite role against the 50%T cases that reduce the excessive deflection of the outlet flow.

Variations in vortex structure of cascades

Due to the tiny geometric dimension of fences, the streamlines on SS are influenced by fences weakly (omitted in Figure 11). According to the limiting streamlines of the Ori and two optimal cases (see in Figure 11), the flow field near the endwall in fenced cascades becomes more complicated than that in the datum cascade. The emergency of the separation lines around the fence configurations is related with the boundary layer separation on the fence surface, which is the outcome of the blockage of strong crossflow by fences. Meanwhile, the crosswise size of the reserve flow in corner region is extended: in the FF case, the reserve flow from FPS intrudes the corner separation region and induces a clockwise spiral point; in the back case, the counter-clockwise spiral lines occur in the original reserve flow region. That indicates the block effect of fence arrays can weaken the endwall crosswise pressure gradient, which makes it hard to withstand the low-energy flow from PS with a higher pressure. Last but not least, the back case has a more extended wake of the fence than the front case, which would play a negative effect on the downstream cascade.

In Figure 12, the contours of streamwise vorticity and the developments of secondary streamlines are depicted on several traverse planes. In the endwall region of the datum cascade, the positive vorticity in red is caused by the boundary layer as well as the PV, and the blue area with negative vorticity is related to the CV. In the region near SS, the negative vorticity represents the CSV and the positive areas in flow passage are corresponding to the WV. The secondary streamlines show that the PV, the CSV and the CV play the most critical role in the vortex structure outside the Ori flow passage. In a word, the optimal fences make the endwall flow structure better. For the vorticity, the fence configurations bring positive vorticity to counteract the endwall boundary layer by means of the FV, which is caused

by the interaction of the fence surface and the crossflow. As a result, the area of endwall negative vorticity is reduced. For the secondary streamlines, the core of the PV is trapped by fences, so it fails to participate in corner separation region. Hence the CV, induced by the PV in 50%T of FF cascade, dissipate in the two optimal fenced cascades when that leave away the TE.

Figure 11 Limiting Streamlines on the Endwall

Figure 12 Distribution of Axial Vorticity and Secondary Streamlines in Blade Passage

Figure 13 shows the secondary flow behaviour visualized by the iso-surface of Q-criteria, which is colored

by vorticity. For the datum cascade, the endwall crossflow transport from the LE of the PS to the corner separation, and the PV, the CSV and the CV mainly organize the flow field exit the passage. Optimal fences block the transportation of crossflow between fences and the PS, and finally reduce the corner separation. Besides that, the PV, of which crosswise actuating range is decreased, directly cause the development of the CV: the CV hard to resist the high-energy flow from the trailing edge of the PS. Therefore, the CV in fenced cascades dissipates in the faster speed and end up earlier.

Figure 13 3D Vortex Structure in Flow Passage

Variations in inflow incidences of cascades

Figure 14 shows the C_{pt} for the datum and the optimum case under six different incidences. At the design Mach number, it is clear that C_{pt} increases with leaving away from the design point. Compared to the curve of the Ori, the fenced case has no reduction in C_{pt} attained in all positive incidences and 0° . For negative incidences, the optimal fence array has stronger control effect with the decrease of incidence. The highest reduction (-29.7%) is reached where the incidence is -9° . Consequently, optimization of the endwall fence configurations to be designed to cover a broader range of operation is still needed.

Figure 14 Total Pressure Loss Coefficient Versus Incidence Angle

CONCLUSIONS

In this study on aerodynamic performance and vortex structure of high-speed compressor cascade with varying locations of fence configurations, numerical analyses are used to derive the following points:

1. At the design point, both the cases of 50%T FF and BF have better aerodynamic performance. The 50%T FF can reduce the total pressure loss coefficient and blockage coefficient by 6.5% and 6.9%, respectively, and increases the absolute value of turning angle by 0.9%. For BF, the 50%T plays better on the reduction of loss and blockage.
2. Both optimal cases of FF and BF can reduce the loss in the endwall region ($0\%H \sim 6\%H$) and the excessive deflection of flow angle in $8\%H \sim 18\%H$. Hence the spanwise uniformity of aerodynamic parameters at the exit is raised.
3. The optimum case brings a positive effect on the cascade by blocking endwall crossflow, delaying the transportation of the PV, and reducing the vorticity of endwall crossflow effectively.
4. The secondary flow on the outlet plane of this high-speed compressor cascade is mainly composed of the PV, the CSV, and the CV. The 50%T FF case, as the optimum endwall fence, not only weakens the PV but also dissipates the CV before the cascade exit, which simplifies the vortex structure and reduces the associated secondary flow loss.
5. Compared to the datum cascade and the optimum cascade, a reduction of the loss exists at negative incidences while an augment occurs at positive incidences. The optimal endwall fence is limited to enlarge the cascade operating range under negative incidences.

NOMENCLATURE

Notation

i	inflow incidence
x	spanwise coordinate
y	pitchwise coordinate
y^+	nondimensional distance from wall
z	streamwise coordinate
A	azimuthal cross section
B	blockage coefficient
C	blade chord length
H	blade span

Ma	Mach number
P	pressure
Q	vortex criterion
T	pitch
V	velocity
Greek	
β	flow angle
δ	inflow boundary layer thickness
ρ	density
Ω	vorticity
Subscripts	
b	blockage region
e	the edge of defect region
in	inlet parameter
out	outlet parameter
s	secondary component
t	stagnation flow parameter
Abbreviations	
BF	back fence(s)
Cp	static pressure coefficient
Cpt	total pressure loss coefficient
CSV	concentrated shedding vortex
CV	corner vortex
FF	front fence(s)
FPS	fence pressure side
FSS	fence suction side
FV	fence vortex
LE	leading edge
Ori	datum cascade
PS	pressure surface
PV	passage vortex
SS	suction surface
TE	trailing edge
WV	wall vortex

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