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Flow control mechanisms of a combined approach using blade slot and vortex generator in compressor cascade

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ABSTRACT

Experiments proved the performance gains in a high-load cascade using a new combined flow control approach, but lack of clear explanations on flow interactions between the configurations and the cascade flow. A detailed discussion is conducted here to further reveal the flow control mechanisms based on experimental and numerical results. An overview of experimental studies is firstly presented to conclude the flow control benefits and to put forward the questions for the simulations. Cascade flow fields observed by experiments show that the combined approach works by two aspects: the slot produces high-speed jets to re-energize the suction side separated flows and reattach them to the suction surface; the vortex generator (*VG*) creates a counter-rotating vortex into cascade passage to further reduce the end-wall cross flows. Thus, both the two main sources of separations in cascade flow are considerably suppressed. The corner separation is suppressed by delaying the passage vortex (P_V): The VG counter-balances and deflects the P_V while the slot jet further limits its pitch-wise width. Coupling the effects of two devices, the cascade flow structure is improved and main vortices are significantly reduced in size and intensity, result in greater separation control effects than the individuals in the high-load cascade.

1. Introduction

Flow control approach is potential to solve contradictions between the high load and wide stability margin [1] in compressors of future aero-engines. Because of large adverse pressure gradient, the high-load compressor encounters more complicated separations and vortices, which generally result in loss and severely limit the stable margin. A flow control approach changes the localized boundary of flow fields and enhances the flow stability, which can suppress separations or stalls in compressors. Therefore, the compressor with flow control applications can fulfill the needs of high load and wide stability margin simultaneously.

Current flow control approaches in compressors can be classified into two types: actuators and geometric configurations. The actuators work by additional input devices that introduce external energy into compressors to suppress separations or stalls. Typical actuators include steady or pulsed jets [2,3], suction [4,5], plasma actuation [6], and acoustic excitation [7], among others. The geometric configurations work by some specialized geometric designs to create self-adapted modifications, which change localized flow fields and reduce separations. Typical geometric configurations include end-wall contouring [8] and fence [9], vortex generator [10–12], and slot jet [13,14], among others. The two kinds of flow control approaches have different advantages, but the industrial utilization of geometric configurations is possible now due to two reasons. Firstly, it needs no additional input devices or energy, and only slightly modifies the compressor without changing the present compressor design system. And secondly, advances in fields of materials and machining make it possible now to adopt the treated surfaces in compressors.

A geometric configuration, the slot jet approach, which is experimentally proved to be very effective on suppressing cascade separations, has been paid much attention. The concept of slot jet was firstly introduced by Rockenbach et al. [13,14] and further developed by Wang at al. [15,16]. Rockenbach et al. reported good performance for the blade row mid-span regions but poor performance near the walls. Wang et al. further investigated the optimal slot geometry in a 2D blade profile by parametrical studies. Ramzi et al. [17,18] concluded the selection rules and the influences of slot parameters. Numerical investigations by Zhou et al. [19] shown great performance gains of the slotted stator in single-stage axial compressor. Experiments conducted recently by Hu et al. [20,21] confirmed the great reduction of the trailing edge separation, but

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Nomenclature

VG	vortex generator	
L	Length of the VG	mm
H	Height of the VG	mm
d_1	VG pitch wise distances to the cascade	mm
d_2	VG axial wise distances to the cascade	mm
α	Deflecting angle of the VG	°
V_Z	Velocity z-component	m/s
BL	Baseline cascade	
Slot	Slotted cascade	
Syn.	Combined flow control configuration	
ω	Total pressure loss $= (P_0^* - P^*)/(P_0^* - P_0)$	
$\Delta\beta$	Flow turning angle $= \beta_{2k}$–β_{1k}	°
C_P	Static pressure rise $= (P - P_0)/(P_0^* - P_0)$	
ΔC_P	Increase of static pressure rise	
S_V	Separation vortex	
C_V	Corner vortex	
CS_V	Concentrated shedding vortex	
SL	Separation line	
SB	Separation bubble	
RL	Reattach line	
P_V	Passage vortex	
VG_V	Vortex induced by the VG	
S_N	Saddle Node	
PS	Pressure side	
SS	Suction side	

Table 1
Design parameters of the high-load cascade.

Parameter/unit	Value
Chord length (C)/(mm)	91.05
Pitch length (S)/(mm)	45
Cascade height (h) (mm)	150
Inlet angle (β_{1k})/(°)	33.46
Outlet angle (β_{2k})/(°)	96.27
Stagger angle (γ)/(°)	25.01
Camber angle (ϑ)/(°)	62.81
Diffusion factor (−)	0.52

the question mentioned by Rockenbach et al. [13] was also found that it was insufficient near the end-wall.

To solve this question, Hu et al. [22] further developed a new combined flow control approach by placing a vortex generator on the end-wall of the slotted cascade, which is used to further reduce the end-wall separations. Experiments by Hu et al. [23] confirmed that the combined approach achieves much better effects than the individual slot jet approach, but the working mechanisms remained to be explained. Therefore, detailed experimental and numerical observations were performed in this paper to further explain the flow control mechanisms of the combined approach.

The paper is organized as follows: At first, the geometric designs of the combined approach are briefly introduced in Sec. 2; Next, the research methods and validations are illustrated in Sec. 3; Then, the results of experimental and numerical explanations on combined flow control mechanisms are presented in Sec. 4; And last, the overall work is concluded in Sec. 5. The main objective of this paper is to conclude the benefits and to explain the working mechanisms of the new combined approach.

2. Geometric model

2.1. High load cascade

A critically high-turning compressor cascade is used in the present study. The cascade is the profile of 10% span of the last row vane in a high-load compressor. The detailed design parameters are listed in Table 1. Similarly to a typical high-load cascade, it has a camber angle of 62.81° and a diffuser factor of 0.52 at the design condition. Therefore, a very complex flow pattern occurs with severe SS separation and end-wall separation, which is a superb case for evaluating the effects of the new combined approach.

2.2. Slot and VG designs

Fig. 1a illustrates the slot parameters and corresponding values which were designed and confirmed by the experiments [23]. The slot inlet and outlet respectively locate at 40%C and 60%C, and the slot width is 1.6 mm. The outlet angle relative to the tangent direction is 15°. The inlet channel turns to the PS by 10° with a convergent angle of 10°. The slot is connected by tangent arc curves to avoid sharp protuberances, which generally induces extra separation and reduces the jet flow effects.

Fig. 1b shows the VG design parameters and corresponding values which were also confirmed by previous experiments. The VG is linearly stacked by NACA64-006 airfoil. Five parameters determine the VG configuration. The VG length (L) is 12 mm and height (H) is 10 mm. Pitch (d_1) and axial (d_2) distances to the cascade are 10.4 mm and 5.6 mm. The deflecting angle (α) to the cascade inflow direction is 24°.

3. Methods and validations

3.1. Measurements

Measurements of the cascade flow were conducted on three planes in the cascade passage to observe the developments of separations. Plane III locates at 1 mm downstream the trailing edge, while Plane II and Plane I moves along negative z-axis in sequence with interval of 1/4 axial chord length. The actual locations will be shown in Fig. 6. The measurements used an L-shape 5-hole probe. The probe was mounted on a 3D moving coordinate frame, which enabled measurements on an assigned 2D plane. Detailed presentations of experiment facilities and procedures were described in the previous paper [23].

Flow parameters on the three planes were acquired to show the stream-wise flow developments in the cascade passage. But measurements on Plane I and II only covered part area of the plane which focused on the corner region due to the probe length limitation. In this study, the cascade separation behaviors and flow structures are considered to preliminarily illustrate the flow control mechanisms and provide validations of the CFD results.

3.2. CFD modeling

To further illustrate the phenomenon observed in experiments, numerical simulations are conducted. The CFX solver is used to solve the 3D steady Reynolds-Averaged Navier–Stokes equations which is closed by k-omega turbulence model. High-resolution, implicit, and time-marching scheme are used. Energy equation and compressibility are taken into account. The Reynolds number is about 3.2×10^5 according to the inlet velocity and chord length.