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Experimental assessment of a new combined flow control approach in compressor cascade

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ABSTRACT

A new combined flow control approach is put forward in this paper using blade slot and vortex generator, which increase the flow control benefits by the combining their effects. A preliminary parameter study is conducted to select the geometry parameters of the vortex generator, and then experiments are performed to assess the gains and to reveal the mechanisms. The measured flow fields show that the cascade separation is significantly reduced and the outlet flow field is more ordered due to the combined approach. The cascade performance, the total pressure loss, the flow turning angle and the static pressure rise averagely increase by −30.9%, +2.0°, and +69.9% respectively. The stable margin of the cascade rises +3° regarding the incidence angle. The mechanisms should be concluded that high-speed slot jet induced reduces trailing edge separations and concentrates remaining separations to the cascade corner, and the vortex generator further decreases the corner separations by deflecting the passage vortex. Combining the benefits of two devices, the combined approach achieves better flow control effects than the individual two.

1. Introduction

Highly loaded compressor contributes to lighter weight and lower fuel consumption in aero-engines. It tends to be the crucial part of the future high efficient and compact compression system. High-load blade requires large camber angle to increase adverse pressure gradient, but it will cause severe separations and complex secondary flow which adversely limit the efficiency and stable margin. So high-load design is contradictory with high efficient or large stable margin. Flow control applications have a great potential to break through this contradiction [1]. Therefore, flow control has been an essential issue in turbomachinery society.

In the past decades, several flow control applications have been introduced into the turbomachinery. According to the working mechanisms, the forms can be classified into two categories. The first one is actuators which operate by external energy inputs. The external inputs directly remove the low momentum separations, such as the steady or pulsed jet [2], the boundary layer suction [3], and the plasma actuation [4], and so on. Actuators usually need external input devices and additional energy consumption. The second one is geometric shapes that operate by some geometric design. The geometric design induces self-adapted modifications to suppress the separation, such as the end-wall contouring [5], the end-wall fence [6], the vortex generator [7–10], and the blade slot [11–15], among the others. Geometric shapes usually need no additional input devices or energy consumption. Both the two type of approaches show potential foreground. But because it needs no external input device or extra consumption, the geometric shape applications are relatively more accessible to realize at present. And it's feasible now to design and manufacture small features on a blade surface. Hence, this paper will focus on the geometric shape applications.

The cascade separation mainly consists of two sources, the trailing edge separation caused by high camber and the corner stall caused by end-wall cross flow. Previous experiments [16] by the authors proved that the slot jet is very effective in reducing the trailing edge separation, but it is not so sufficient in reducing the corner stall. The slot jet pushes remaining separations closer to the end wall, but only slightly reduces them. The studies on vortex generator (VG) [9,10] provides a solution for this insufficiency. The VG, which can suppress the end wall cross flow, is potential to further delay the concentrated end-wall separations in the slotted cascade.

Under this consideration, this paper develops a new combined flow control approach via coupling the effects of the slot jet and the VG. On the basis of slot jet approach [16], a VG is added to the slotted cascade

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Nomenclature

C	chord
C_p	static pressure rise coefficient = $(P-P_{in})/(P_{0in}-P_{in})$
LE	leading edge
i	incidence angle
P	local pressure
P_0	total pressure
P_{in}	inlet pressure
TE	trailing edge
VG	vortex generator
ω	total pressure loss coefficient = $(P_{0in}-P_0)/(P_{0in}-P_{in})$
$\Delta\beta$	flow turning angle = $\beta_{2k}-\beta_{1k}$
δ	thickness of inlet boundary layer
β_{1k}	inflow angle
β_{2k}	outflow angle

configuration for further reducing the end-wall separations. Measurements are performed to show separation behaviors, loss characteristics and performance of the cascade. The objective is to assess the effects of the combined approach and preliminarily explaining mechanisms. The new approach may contribute to an original idea for the more powerful flow control techniques in highly loaded compressor cascades.

2. Experimental setup

2.1. Experiment facilities

The cascade experiments were conducted on an open-circuit low-speed linear cascade wind tunnel which is driven by an axial blower powered by an electromotor. Fig. 1a presents the cascade test rig and the schematic of the test section. The blower draws in air from the atmosphere and discharges to the test section through guide duct and chamber. The cascades are mounted on replaceable tailboards to fit with different cascade profiles. The tailboards are mounted on a rotating disk which enables a continuously change of the incidence angle by rotary. Seven blades are used to ensure the flow periodicity while the middle one is measured. The flow periodicity is confirmed by the blade wake over the middle three passages.

The wind tunnel is designed for the maximum inflow velocity 0.3 Ma and incidence angle ± 25°. The inflow turbulence intensity is about 1% at the test section inlet. The wind tunnel inflow condition is measured before mounting cascades as shown in Fig. 1b, which shows a 16 mm thickness of the boundary layer approaching the cascade inlet section (about 10% of the blade height). The cascades and the tailboards are manufactured using the organic glass which is relatively cheap and easy to ensure the surface smooth. In this study, the operating inflow velocity maintains 51 m/s for different conditions. The experiments measure the incidence angle from -3° to 6° at a Reynolds number of 0.5×10^{6} based on the inflow velocity and cascade chord length.

2.2. Measurement procedure

The inflow measuring section locates at 50 mm upstream of the blade with total pressure, static pressure, and total temperature transducers. The actual value of each parameter is the average of 5 sensors. The outflow conditions are measured using a moving five-hole L-shape probe as shown in Fig. 2. The probe is mounted on a movable 3D coordinate frame which enables the probe a continuous movement on the specified 2D plane. The coordinate frame movements are defined by a programmable logic controller. In the present study, the 2D flow fields (x-y plane) are measured on four axial locations (z-axis).

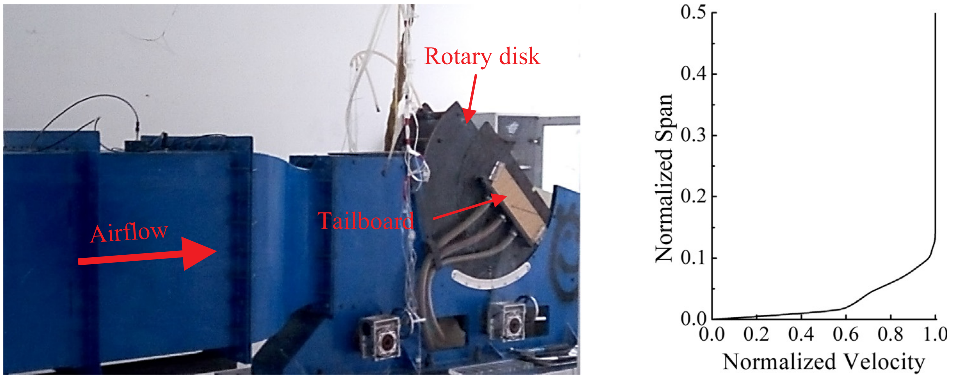
The measurement planes are shown in Fig. 2. The Plane I locates at about the middle of the cascade axial chord length, and the Plane III locates at the cascade trailing edge. Along z-axis, the Plane II locates at 20 mm upstream the Plane III, and the Plane I locates at 20 mm upstream the Plane II, and the Plane IV locates at 30 mm downstream the Plane III. At the Plane I, Plane II, and Plane III, the flow field details are measured to illustrate the flow control mechanisms. At the Plane IV, the cascade performance is mainly focused on to assess the flow control effects.

The measured contours show that the flow loss distribution is very coincident at the span-wise two symmetric sections, and their averaged loss has a difference of 1.3%, indicating that the cascade flow is approximately symmetric. So it's sufficient to measure the flow field only over half of the span. The resolution of data acquisition are also validated by two resolutions, the coarse resolution and the fine resolution. The cascade loss characteristics agree well with each other, so the coarse resolution already fulfills the requirements of measurement resolution. To acquire more flow details, the fine grid is used in this study.

The relative error limits of the velocity, the total pressure loss coefficient, and the static pressure rise coefficient are 1%, 2.5% and 2.5% respectively, while the error limits of the flow turning angle is 1°.

3. Combined approach design

The baseline cascade is a highly loaded cascade which is the profile of 10% span section of the last row stator vanes of an axial critically



(a) Cascade test rig (b) Inflow velocity profile

Fig. 1. Cascade test rig and inflow boundary layer condition.