Effects of Plasma Aerodynamic Actuation on Corner Separation in a Highly Loaded Compressor Cascade*

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Abstract This paper reports experimental results on the effects of plasma aerodynamic actuation (PAA) on corner separation control in a highly loaded, low speed, linear compressor cascade. Total pressure loss coefficient distribution was adopted to evaluate the corner separation control effect in wind tunnel experiments. Results of pressure measurements and particle image velocimetry (PIV) show that the control effect of pitch-wise PAA on the endwall is much better than that of stream-wise PAA on the suction surface. When both the pitch-wise PAA on the endwall and stream-wise PAA on the suction surface are turned on simultaneously, the control effect is the best among all three PAA types. The mechanisms of nanosecond discharge and microsecond discharge PAA are different in corner separation control. The control effect of microsecond discharge PAA turns out better with the increase of discharge voltage and duty cycle. Compared with microsecond discharge PAA, nanosecond discharge PAA is more effective in preventing corner separation when the freestream velocity increases. Frequency is one of the most important parameters in plasma flow control. The optimum excitation frequency of microsecond discharge PAA is 500 Hz, which is different from the frequency corresponding to the case with a Strouhal number of unity.

Keywords: plasma aerodynamic actuation, corner separation, compressor, cascade

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(Some figures may appear in colour in the online journal)

1 Introduction

Corner separation, which forms over the suction surface and endwall corner of a blade passage, induces passage blockage and considerable total pressure loss. As the stage loading is increased, the flow in the stator passage breaks down firstly due to large corner separation, which significantly impairs the stage efficiency [1]. Thus, corner separation control is one of the important ways to improve the axial compressor stability and efficiency.

Nowadays, many mechanical and aerodynamic methods are successfully adopted to control the separated flows in compressors and cascades, such as casing treatment [2,3], vortex generator [4], boundary layer suction [5,6], synthetic jets [7], etc.

Our approach to control the corner separation is plasma aerodynamic actuation (PAA), which is promising in improving aircraft aerodynamic characteristics and propulsion efficiency [8–16]. A plasma aerodynamic actuator, which consists of electrode pairs separated by a thin dielectric insulator, has the merits of robustness, simplicity, low power consumption and real-time control at high frequency. PAA has drawn considerable attention for axial compressor stability extension [17]. Steady and unsteady microsecond discharge PAA only on the blade suction surface has been used to control the corner separation in a low speed compressor cascade [18–20].

The objective of our research is to optimize the PAA arrangement and better understand the mechanism of plasma flow control in a highly loaded, low speed, linear compressor cascade, for the purpose of achieving a better control effect. Also, nanosecond discharge PAA and PIV measurements are used for the first time in corner separation control.

2 Experimental setup

2.1 Compressor cascade facility

Experiments are carried out on a low speed compressor cascade facility, which consists of five highly loaded controlled diffusion airfoils (CDA) made of organic glass, as shown in Fig. 1. The detailed design parameters of the cascade are listed in Table 1. The incoming flow is straightened, accelerated and passes
through a series of wire-mesh grids to generate a uniform flow field at the test section inlet. The freestream turbulence is within 0.6% and the thickness of the laminar boundary layer on the endwall is about 8 mm, 5.3% of the blade span.

![Cascade Wind Tunnel](image1.png)

Fig. 1 The compressor cascade facility

Table 1. Main parameters of the compressor cascade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord (c)</td>
<td>100 mm</td>
</tr>
<tr>
<td>Span (h)</td>
<td>150 mm</td>
</tr>
<tr>
<td>Turning angle (∆β)</td>
<td>60 deg</td>
</tr>
<tr>
<td>Inlet flow angle (β₁)</td>
<td>145 deg</td>
</tr>
<tr>
<td>Outlet flow angle (β₂)</td>
<td>85 deg</td>
</tr>
<tr>
<td>Stagger angle (γ)</td>
<td>104.87 deg</td>
</tr>
<tr>
<td>Chord to pitch ratio</td>
<td>1.67</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum thickness to chord ratio</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Only the middle blade is furnished with the plasma aerodynamic actuator. Total and static pressures at 20 mm, 20% of the chord length, upstream of the blade leading edge are measured. Total pressure distributions at 30 mm downstream of the blade trailing edge at different blade spans are measured. A five-hole probe calibrated for pitch and yaw is used to measure the total pressure at the cascade exit. The uncertainty is calculated to be 0.8% of the measured pressure in which the digital quantization and calibration errors are included.

Two parameters, total pressure loss coefficient ω and relative reduction of the pitch-averaged total pressure loss coefficient δ(ω), are used to quantify the control effect of PAA on flow separation.

The total pressure loss coefficient ω for a blade passage is defined as

\[ ω = \frac{P_{t1} - P_{t2}}{P_{t1} - P_{s1}}. \]  

(1)

The pitch-averaged total pressure loss coefficient \( \overline{ω} \) is defined as

\[ \overline{ω} = \frac{P_{t1} - \overline{P_{t2}}}{P_{t1} - P_{s1}}. \]  

(2)

The relative reduction of the pitch-averaged total pressure loss \( δ(\overline{ω}) \) is defined as

\[ δ(\overline{ω}) = \frac{\overline{ω}_{\text{baseline}} - \overline{ω}_{\text{actuated}}}{\overline{ω}_{\text{baseline}}} \times 100\%. \]  

(3)

where \( P_{s1}, P_{t1} \) and \( P_{t2} \) are the static pressure at the cascade inlet, total pressure at the cascade inlet and total pressure at the cascade exit, respectively.

2.2 PIV setup and image acquisition

A commercial PIV system, developed by the LaVision Incorporation, is employed in the measurements of flow structures in quiescent air and cascade passages, as shown in Fig. 2. The light source is a dual cavity Nd: YAG laser, and the maximum illumination energy is 135 mJ/pulse at a 15 Hz repetition rate. The images are captured with a high-resolution CCD camera (1680×1280 pixels), which is arranged normal to the test section. The experimental uncertainty for PIV is about 0.12 m/s for the most unfavorable case.

![PIV Setup](image2.png)

Fig. 2 PIV setup

In order to offer maximum movability and freedom to transport the laser light from the laser head to the test section, a laser guiding arm is used, which consists of 2 standard distal end connectors and 7 mirror arrangements with sizes of 25.4 mm diameter, 3 mm thickness with high LDT coatings. The fields of view cover nearly the whole cascade passage from the blade leading edge to the trailing edge and from the pressure surface to the neighboring suction surface. A piece of organic glass plate is replaced with an optical glass plate to gain higher light transmission. Images of test sections at different spans are acquired by adjusting the position of the laser head in the span-wise direction. The quiescent air for induced flow characteristics by PAA is seeded with vaporized mineral oil with a mean size of about 0.3 μm. The flow in the compressor cascade is seeded with mixed glycerol oil droplets, which are evaporated and condensed with a smoke generator. The range of the particle size is 1-2 μm and can follow the gas velocity oscillation.
2.3 PAA arrangement

A schematic of an asymmetric plasma aerodynamic actuator is shown in Fig. 3. The dielectric layer is a Kapton tape with a relative permittivity constant of 2.5. The electrodes are made of copper. The main geometric parameters are summarized as follows: \( d_1 = 3 \text{ mm}, \quad d_2 = 3 \text{ mm}, \quad \Delta d = 1 \text{ mm}, \quad h_d = 0.24 \text{ mm} \) and \( h_e = 0.035 \text{ mm} \), respectively.

The PAA is energized by two high voltage RF power supplies. When an AC input high voltage is supplied on the electrodes and the AC amplitude is large enough, the air near the electrodes is weakly ionized. A microsecond pulsed power supply is used to generate microsecond discharge PAA. The output waveform is a sine wave. The output ranges of peak-to-peak voltage and driving frequency of the power supply are 0-40 kV and 6-40 kHz, respectively. A nanosecond pulsed power supply is used to generate nanosecond discharge PAA. The ranges of output voltage and frequency are 5-80 kV and 0.1-5 kHz, respectively.

The discharge voltage and current are measured by a high voltage probe (Tektronix P6015A) and a current probe (Tektronix TCP312+TCPA300). Signals are recorded on an oscilloscope (Tektronix DPO4104). The measurement uncertainties of output voltage and frequency are \( \pm 0.2 \text{ kV} \) and \( \pm 0.2 \text{ kHz} \), respectively.

Three types of PAA are designed, as shown in Fig. 4(a)-(c). Type I is stream-wise PAA on the suction surface, with plasma aerodynamic actuators located at 10\%, 30\% and 80\% of the chord length, respectively. Type II is pitch-wise PAA on the endwall, with plasma aerodynamic actuators located at 20\% and 80\% of the pitch, respectively. Type III is a combined actuation of pitch-wise PAA on the endwall and stream-wise PAA on the suction surface, with plasma aerodynamic actuators located at the same positions as type I and II PAA. The discharge image of pitch-wise PAA on the endwall is given in Fig. 5.

3 Results and discussion

3.1 PIV results in quiescent air

Voltage-current curves of microsecond and nanosecond discharge PAA are shown in Fig. 6. Their discharge voltage and frequency are 14 kV, 1 kHz and 11 kV, 1 kHz, respectively. The maximal discharge currents of microsecond and nanosecond discharge PAA are 0.2 A and 4 A, which indicate that the actuation strength of nanosecond discharge PAA is much larger than the former.

As seen from Figs. 7 and 8, the induced flow characteristics of microsecond and nanosecond discharge PAA
measured by PIV in quiescent air are dramatically different. For microsecond discharge PAA, a starting vortex appears and then evolves into a wall jet, inducing high-energy fluids of the main flow to the solid surface boundary layer near the electrodes of actuators. The starting vortex exists for less than 3 s and the wall jet is 50 mm downstream of the upper electrode, which can energize the boundary layer flow to withstand the adverse pressure gradient and prevent flow separation. The maximal velocity of the wall jet is located within the height of 5 mm from the actuator surface, but the maximal vorticity is located between the height of 5-15 mm. For nanosecond discharge PAA, the induced airflow moves upwards due to the strong shock wave during a quite short time scale of the nanosecond magnitude. The original discharge status of the interaction between plus and minus vorticities near electrodes at $T=1/12$ s generates a strong air convection normal to the actuator surface, which decides the induced flow characteristic. Besides, the vorticity and airflow velocity induced by microsecond discharge PAA are greater than those induced by nanosecond discharge PAA.

3.2 Flow structure in a cascade blade passage

Apparent separated flows and shedding vortex on the suction surface appear at 50% of the blade span when the freestream velocity is 30 m/s (corresponding $Re$ is 134,500) and the angle of attack is 0 deg, as shown in Fig. 9. Point S is the starting point of flow separation on the suction surface, where the reversed flow under a high adverse pressure gradient interacts with the incoming flow. The shedding vortex emerges at $T = 80$ ms, develops greatly at 160 ms and disappears at 240 ms, during which the shedding vortex induces the main flow to interact with the low-energy fluids of flow separation on the suction surface. The vorticity in the cascade passage increases by 20% with the appearance of the shedding vortex, but recovers to a normal level when the shedding vortex disappears.
3.3 Effect of the PAA on the separated flows

Effects of steady and unsteady microsecond discharge PAA on the separated flows are investigated with type I PAA, as shown in Fig. 10. An additional vortex is generated near the second pair of electrodes, and the vortex scale induced by steady PAA is much larger than that by unsteady PAA. The induced vortex interacts with the separated flows and the shedding vortex, then the flow separation structure on the suction surface is destroyed and the vorticity is reduced by 42%. The effects of the first and third pairs of electrodes are weaker than the second pair, indicating that the optimal location of PAA on the suction surface is near the starting point S of flow separation.

3.4 Effect of the PAA on the total pressure loss

Effects of PAA with different actuation parameters on corner separation are explored when the freestream velocity is 50 m/s (corresponding $Re$ is 223,000) and the angle of attack is 0 deg.

3.4.1 Discharge voltage

The PAA strength, which is directly related to the discharge voltage and numbers of electrode pairs, is an important parameter in plasma flow control. Effects of discharge voltage on the total pressure loss at 70% of the blade span are investigated with a type II PAA, as shown in Fig. 11. As the discharge voltage increases from 0 kV to 13 kV, the PAA strength increases gradually, and starts to increase while the discharge voltage reaches 4 kV and keeps constant until 12 kV. The maximal $\delta(\bar{\gamma})$ is up to 10.2%. Therefore, increasing the discharge voltage is an important method of enhancing the control effect on corner separation, but higher discharge voltage leads to earlier destruction of the dielectric material and a higher power consumption requirement.
3.4.2 Duty cycle

Since unsteady PAA can induce large coherent vortical structures and generate unsteady disturbances to prevent or delay the onset of flow separation, the control effect can be enhanced. Unsteady PAA for separation control of airfoil profile has been investigated experimentally [21]. The result shows that unsteady PAA has shorter time scale and can enhance the capability of flow control.

Fig. 12 documents the distribution of $\delta(\omega)$ at 50%, 60% and 70% of the blade span within the ranges of duty cycle from 20% to 100% while the unsteady excitation frequency is fixed at 500 Hz. The control effects of unsteady PAA increase gradually as the duty cycle changes from 20% to 80% and the maximum $\delta(\omega)$ at the three blade spans are 5.6%, 6.2% and 11.4%, respectively. However, the control effect of unsteady PAA is weaker than that of steady PAA when the duty cycle is less than 40%.

3.4.3 Excitation frequency

The excitation frequency of PAA is one of the most important parameters in unsteady flow control, and believed to be the best for preventing the flow separation in a turbine cascade when the Strouhal number is near unity [22]. Therefore, effects of excitation frequency are performed to determine if such an optimum frequency exists for the unsteady PAA used in controlling corner separation in a highly loaded compressor cascade.

$$F^+ = f_{\text{sep}} / v_\infty,$$  \hspace{1cm} (4)

where $f$ is the excitation frequency, $c_{\text{sep}}$ is the characteristic length of flow separation region and $v_\infty$ is the freestream velocity.

The length of separation region, based on corresponding numerical results [23], is 75% of the chord length when the freestream velocity is 50 m/s. Therefore, the optimum excitation frequency is calculated to be 667 Hz according to the Strouhal number of 1. However, the optimum excitation frequency obtained in experiments is 500 Hz and the corresponding Strouhal number is calculated to be 0.75, as shown in Fig. 13, which is different from plasma flow control on a turbine cascade. Therefore, the optimal excitation frequency changes greatly with the flow situation, experimental model and PAA type.

3.4.4 PAA types

Fig. 14 shows the distribution of $\omega$ at 70% of the span when the three PAA types are applied. $\delta(\omega)$ decrease by 2.9%, 8.1% and 12.4%, respectively. The control effect of type III PAA is the best among the three PAA types because of their different mechanisms. The stream-wise PAA on the suction surface induces the boundary layer to accelerate and delays the occurrence of separation. The pitch-wise PAA on the endwall induces airflow to move in the opposite direction to cross flow. When the PAA both on the suction surface and endwall are turned on, the cross flow on the endwall and boundary layer flow separation on the suction surface can be prevented simultaneously. Therefore, the control effect of combined PAA is much better than other PAA types.

3.4.5 Discharge form

Effects of microsecond and nanosecond discharge PAA on corner separation at a high freestream velocity of 95 m/s and a high angle of attack of 3° are investigated with type II PAA. Distributions of $\omega$ at 70% of the blade span are given in Fig. 15. $\delta(\omega)$ decrease by $-0.3\%$, 1.9% and 7.6% with steady, unsteady microsecond discharge PAA and nanosecond discharge PAA. The control effect of microsecond discharge PAA with high freestream velocity is much weaker than that of nanosecond discharge PAA, and even becomes negative with steady microsecond PAA. Therefore, nanosecond discharge PAA is more efficient in preventing corner separation than microsecond discharge PAA.
4 Conclusion

Corner separation, which forms over the suction surface and endwall corner of a blade passage, causes significant total pressure loss in a highly loaded compressor cascade. Both microsecond and nanosecond discharge PAA are effective in corner separation control, but the actuation strength of nanosecond discharge PAA is much larger than microsecond discharge PAA. When microsecond discharge PAA is turned on, a starting vortex appears and then evolves into a wall jet, but for nanosecond discharge PAA, the induced airflow moves upwards due to the strong shock wave. Duty cycle and excitation frequency are key parameters in unsteady plasma flow control. The main effect of span-wise PAA on the endwall is to inhibit the cross flow from a neighboring pressure surface to the suction surface, while the main effect of stream-wise PAA on the suction surface is to inhibit the boundary layer accumulation and separation. Pitch-wise PAA on the endwall and combined PAA are much more efficient than stream-wise PAA on the suction surface.

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