Plasma Flow Control in Axial Flow Compressors (Postprint)

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Abstract

The author was among the early researchers internationally to conduct investigations on plasma flow control in axial compressors. Through nearly a decade of research accumulation, a relatively profound understanding of plasma flow control for axial compressors has been established. This paper first briefly presents partial research progress on plasma flow control in axial compressors: taking compressor cascades as the research object, the patterns and mechanisms of plasma actuation in suppressing tip leakage flow are analyzed; through numerical simulation and experiments, the flow control patterns and mechanisms of plasma actuation on stall in high-load axial compressors are investigated; taking high-speed compressor cascades as the research object, the flow control patterns of plasma actuation on the suction surface and endwall on three-dimensional corner separation in high-speed compressors are explored; then the concept of plasma-actuated compressors is introduced; finally, prospects for future research work are provided.

Full Text

Preamble

Plasma Flow Control of Axial Compressors

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Abstract: The authors were among the first internationally to conduct research on plasma flow control in axial compressors. Through nearly a decade of investigation, a profound understanding of plasma flow control mechanisms in axial compressors has been established. This paper first presents selected research progress on axial compressor plasma flow control: analyzing the laws and mechanisms of plasma actuation for tip leakage flow suppression in compressor cascades; investigating flow control laws and mechanisms for high-load axial compressor stall through numerical simulation and experiments; exploring suction surface and endwall plasma actuation for controlling three-dimensional corner separation in high-speed compressor cascades; introducing the concept of plasma-actuated compressors; and finally providing an outlook for future research.

Keywords: axial compressor; plasma flow control; tip leakage flow; stall; three-dimensional corner separation; plasma-actuated compressor

The internal flow within compressors is extremely complex. In the endwall region, multi-scale vortical structures with varying intensities exhibit different pulsation and propagation characteristics. Their interactions with each other, the mainstream flow, and solid walls result in strongly unsteady, three-dimensional, multi-frequency, and multi-scale flow phenomena that adversely affect compressor performance. Modern aero-engine compressors feature continuously increasing loading, where strong adverse pressure gradients lead to more complex secondary flows and separation structures [1, 2], often causing significant flow losses and blockage. Maintaining required efficiency and aerodynamic stability becomes exceptionally challenging.

To ensure high-efficiency operation and aerodynamic stability in high-load compressors, numerous aerodynamic design approaches have been attempted, such as low aspect ratio and high solidity designs, swept and leaned blade profiles, and tandem airfoils [3]. Since these passive control measures struggle to effectively control complex internal flows across the entire engine operating envelope, relying solely on them to break through compressor loading limits remains a formidable challenge. Consequently, active flow control techniques originally developed for external flows have been applied to high-load compressor design.

Traditional active flow control techniques, such as blowing/suction, often suffer from complex mechanical structures, heavy driving devices, and limited excitation bandwidth and response speed, making them unsuitable for aero-engine applications. In contrast, plasma flow control technology offers advantages including simple structure, low power consumption, fast response, and wide excitation bandwidth [4-6], making its application to controlling complex flows within compressors theoretically significant and valuable for engineering applications [5-7].

In 2007, Wu et al. [8] first experimentally demonstrated internationally that plasma actuation could improve compressor stall margin. Subsequently, Vo et al. [9-11] and Jothiprasad and Wadia et al. [12, 13] investigated stall suppression mechanisms through numerical simulation. Vo et al. [9-11] reported that plasma actuation located near the rotor tip leading edge was significantly more effective at suppressing stall than actuation at the trailing edge, with the primary mechanism being downstream movement of the mainstream/leakage flow interface, thereby suppressing tip leakage flow spillage from adjacent blade leading edges. Jothiprasad and Wadia et al. [12, 13] compared different actuation angles, finding that axial-force-producing plasma actuation was substantially more effective for stall control than circumferential-force-producing actuation. Contrasting with Vo et al.' s explanation, they associated stall suppression with reduced rotor tip loading coefficients. Li Gang and Li Zhiyuan et al. [14, 15] also conducted simulation studies on plasma actuation for stall suppression, noting that actuation primarily increased mainstream momentum to push the mainstream/leakage flow interface downstream, inhibiting leakage flow spillage from the blade leading edge. Wu et al. [16] numerically investigated unsteady plasma actuation effects, demonstrating that actuation at 0.25, 0.5, and 1 times the blade passing frequency could couple with tip leakage vortices, achieving better control than steady actuation.

Experimentally, Vo et al. [11] initially verified plasma actuation' s ability to suppress compressor stall in a non-metallic compressor. Saddoughi et al. [17] used plasma actuation to increase transonic compressor stall margin by 4%, with unsteady actuation proving more effective than steady actuation, and axial actuation outperforming incidence angle actuation. The study concluded that plasma actuation did not significantly alter compressor characteristics during stable operation, with stall margin improvement primarily stemming from effects on the unsteady characteristics of rotor tip leakage flow.

In 2009 and 2010, Li Yinghong and Wu et al. [18, 19] first experimentally and numerically investigated plasma actuation for suppressing three-dimensional corner separation in low-speed compressor cascades. By positioning plasma actuators on the blade suction surface, Li Yinghong, Wu Yun et al. [20] found that both steady and unsteady plasma actuation could effectively reduce cascade three-dimensional corner separation losses, with unsteady actuation demonstrating superior performance. Subsequently, Zhao Xiaohu conducted detailed experimental and numerical studies on the laws and mechanisms of three-dimensional corner separation suppression using a low-speed, high-load compressor cascade.

In 2011, Zhao Xiaohu et al. [21] experimentally studied suction surface plasma actuation for high-load compressor cascade corner separation, identifying optimal actuator placement near the separation onset point, with an optimal excitation frequency of 450 Hz (corresponding to a dimensionless frequency of 0.75). Zhao Xiaohu et al. [22] subsequently revealed the suppression mechanism through numerical simulation combined with flow topology analysis. In 2012, Wu et al. [23] found through experiments and numerical simulation that endwall plasma actuation was more effective than suction surface actuation for suppressing three-dimensional corner separation, while combined suction surface and endwall actuation provided even better suppression. Zhao Qin et al. [24] experimentally investigated endwall plasma actuation for high-load compressor cascade corner separation and explored nanosecond pulsed plasma actuation capabilities. Zhao Xiaohu et al. analyzed endwall plasma actuation [25] and combined actuation layouts [26, 27] in detail. In 2014, Zhang Haideng et al. [28] conducted comprehensive optimization studies on various actuation layouts to identify optimal configurations for suppressing three-dimensional corner separation.

After 2014, the authors' research group began exploring nanosecond pulsed plasma actuation for controlling three-dimensional corner separation in high-speed, high-load compressor cascades (referred to as "high-speed" herein). Initial experimental studies revealed that nanosecond pulsed plasma actuation could significantly affect the suction surface boundary layer, improving two-dimensional profile losses [29]. To obtain actuation layouts capable of suppressing high-speed compressor cascade three-dimensional corner separation, Zhang Haideng et al. conducted investigations on internal flow structures [30, 31], nanosecond pulsed plasma actuation characteristics [32], and coupling mechanisms between actuation and three-dimensional corner separation [33]. In summary, under high-speed conditions, suppressing high-load compressor three-dimensional corner separation faces greater challenges, and effective suppression is difficult to achieve without clear understanding of the flow control mechanisms for either sinusoidal or nanosecond pulsed plasma actuation.

Domestically, Li Gang et al. [34] and Liu Huaping et al. [35] also studied plasma actuation for suppressing compressor cascade three-dimensional corner separation, analyzing control mechanisms and verifying effectiveness. Internationally, De Giorgi et al. [36, 37] explored plasma actuation for three-dimensional corner separation suppression, while Akcayoz et al. [38] published related results in 2016, noting that suction surface plasma actuation was more effective than endwall actuation for reducing blade passage flow losses, with optimal control achieved when actuators were positioned near the upstream region of corner separation onset.

This paper presents research progress from the authors' group on typical approaches for axial compressor plasma flow control, analyzing flow control laws and mechanisms to demonstrate potential technical advantages and future development trends, and finally introducing the concept of plasma-actuated compressors.

1 Plasma Flow Control of Compressor Tip Leakage Flow

To understand the laws and mechanisms of plasma flow control for compressor tip leakage flow, the rotor tip airfoil was selected for numerical simulation. The study first examined control laws for flow losses and blockage caused by tip leakage flow in a cascade environment, then analyzed suppression mechanisms by investigating effects on leakage flow rate and axial momentum in the tip flow field, and finally conducted preliminary experimental validation of the conclusions.

1.1 Research Object and Numerical Simulation Method

The compressor cascade model is shown in [Figure 1: see original paper], with main aerodynamic parameters provided in . Numerical simulations employed the commercial CFD software Ansys CFX with a second-order high-precision difference scheme. Computational grids were generated using Autogrid with an O-4H topology, featuring OH-type grids at the tip clearance region. Grid structure and boundary conditions are illustrated in [Figure 2: see original paper]. Based on grid independence verification, the simulation used 3.6 million total grid cells with local refinement near walls to ensure y+ < 2. Hub, casing, and blade surfaces were modeled as adiabatic no-slip walls. To reduce three-dimensional corner separation effects near the hub on tip leakage flow, boundary layer suction was applied upstream of the profile side blade, with suction rates consistent with experimental conditions.

Simulations specified an inlet velocity of 43 m/s based on experimental conditions, corresponding to a Reynolds number of 3×10 based on blade chord length. Inlet flow angle was maintained at 0° incidence, with back pressure specified at the outlet and periodic boundary conditions applied in the pitchwise direction.

To ensure numerical reliability, turbulence models were first validated. Comparative analysis revealed that the k- model could reasonably capture complex endwall flows in the cascade passage, thus it was adopted for all simulations.

A typical dielectric barrier discharge plasma actuator is shown in [Figure 3: see original paper], featuring upper and lower electrodes separated by a dielectric barrier. The upper electrode connects to the power supply positive terminal, while the lower electrode connects to the negative terminal. When energized, air above the lower electrode ionizes to form plasma. Charged particles in the plasma migrate under the electric field and collide with neutral molecules, generating a body force acting on surrounding gas. In numerical simulations, the phenomenological model of Suzen et al. [39] was used to solve for the body force induced by plasma actuation, which was then applied as a boundary condition in the cascade flow field.

1.2 Plasma Actuation Layout

[Figure 4: see original paper] shows the distribution of near-wall jet velocity induced by two plasma actuators in quiescent air under different actuation strengths. When a single actuator generates a body force of 50 mN/m, the maximum induced velocity reaches 4.5 m/s, achievable with existing plasma actuators and ensuring experimental validation of the numerical results.

As shown in [Figure 5: see original paper], actuators were arranged parallel to the cascade front line, creating axial body force expected to increase axial momentum in the tip flow field and suppress leakage vortex development toward the blade leading edge and adjacent blade pressure surface. In this layout, Dis is defined as the distance between the upper/lower electrode interface of Actu2 and the blade leading edge, with negative values indicating actuator position upstream of the leading edge.

1.3 Plasma Actuation Effects on Tip Leakage Flow Suppression

The total pressure loss coefficient is defined as:

$$\omega = \frac{p_{1t} - p_2}{p_{1t} - p_{1s}}$$

where p_{1t} is inlet total pressure, p_{1s} is inlet static pressure, and p_2 is local total pressure.

The mass-flow-averaged total pressure loss coefficient at a section is:

$$\bar{\omega} = \frac{\int_S \omega \rho u \, dS}{\int_S \rho u \, dS}$$

where S is the selected cross-sectional area and u is axial velocity.

The pitchwise-averaged total pressure loss coefficient is:

$$\omega_p = \int_{-t/2}^{t/2} \omega \, dy$$

Following Suder’ s work [40], for the incompressible flow studied here, regions where $C_{\text{value}} > 2$ on a selected section are defined as blockage regions. According to Suder, blockage regions are not sensitive to the specific C_{value}; here $C_{\text{value}} = 2$ is used. The blockage coefficient at a point on a section is defined as:

$$\text{coeffi}_{\text{block}} = 1 - \frac{u_{\text{loc}}}{u_e}$$

where u_{loc} is local axial velocity and u_e is axial velocity at the nearest blockage boundary. The section-averaged blockage coefficient is then defined accordingly.

[Figure 6: see original paper] shows the effects of plasma actuation on mass-flow-averaged total pressure loss and section-averaged blockage coefficient at the cascade outlet under different actuation strengths and positions. Positive relative change indicates reduction in the corresponding flow parameter by plasma actuation, with body force values representing those generated by a single actuator. According to [Figure 6: see original paper], as actuators move from 30% chord upstream of the blade leading edge toward downstream positions, the relative changes in flow loss and blockage first increase then decrease. Maximum reduction in outlet flow loss and blockage occurs when actuators are positioned 20% chord downstream of the leading edge. Actuation strength affects the magnitude of loss and blockage changes but does not alter the optimal actuator position or the variation pattern with position.

[Figure 7: see original paper] presents pitchwise-averaged casing wall axial shear stress at different axial positions within the cascade passage. The 0% chord axial position represents the blade leading edge. The location where pitchwise-averaged casing axial shear stress transitions from positive to zero characterizes the average axial position of the mainstream/leakage flow interface [41]. According to [Figure 7: see original paper] and [Figure 6: see original paper], the optimal flow control position lies within 5% chord upstream of the average mainstream/leakage flow interface axial position, indicating that actuation near the upstream region of this interface provides the strongest tip leakage flow suppression. Cameron et al. [41] showed that the average mainstream/leakage flow interface position at near-stall conditions typically reaches near the blade leading edge. Vo et al. [9] demonstrated that plasma actuation near the rotor tip leading edge was most effective at suppressing compressor stall. Combined with the present results, it can be inferred that actuation near the rotor tip leading edge effectively suppresses leakage flow at near-stall conditions, thereby possessing strong stall suppression capability.

1.4 Plasma Actuation Effects on Tip Axial Momentum

According to Cameron et al. [41], the key factor determining the mainstream/leakage flow interface position is the axial momentum of mainstream and leakage flows at the blade tip. To prevent upstream movement of this interface, plasma actuation should maximize axial momentum in the tip flow field. This section analyzes the relationship between leakage flow suppression and the ability to increase tip flow axial momentum.

A control volume analysis method was adopted from reference [42]. [Figure 8: see original paper] shows the blade tip control volume model and its dynamic analysis. The control volume height was determined based on the spanwise extent of leakage flow influence at the cascade outlet, while its axial width was set to 1% chord length. With periodic boundary conditions in the pitchwise direction, momentum exchange with the surroundings occurs through surfaces A1, A2, and U. Surface C connects to the casing wall with no momentum flux. External forces on the control volume include surface pressures p_1, p_2, p_c, and p_u on surfaces A1, A2, C, and U, respectively, while plasma actuation and blade effects are combined as body force F_b. Applying the momentum theorem yields:

$$\int_{A1} p_1\, dS + \int_{A2} p_2\, dS + \int_{C} p_c\, dS + \int_{U} p_u\, dS + F_b = \frac{d}{dt}\int_{V} \rho u_a\, dV$$

The left side represents the net external force on the control volume, while the right side represents momentum change, with subscript a denoting axial direction. Taking the incoming flow direction as positive, a positive right side indicates net axial force directed downstream, while negative indicates upstream force. Denoting the control volume at the blade leading edge as Control Volume 1 and numbering downstream volumes sequentially, the cumulative axial momentum change for the j-th control volume is defined as:

$$M_j = \sum_{i=1}^{j} m_i$$

where m_i is the momentum change in the i-th control volume. M_j reflects the cumulative effect of axial momentum changes, showing an increasing trend when net axial forces remain downstream-directed and decreasing when forces become upstream-directed. Compared to m_i, M_j more intuitively reflects axial momentum variation patterns.

[Figure 9: see original paper] shows the distribution of blade tip flow field axial momentum accumulation under baseline conditions and with plasma actuation at different positions (single actuator body force = 50 mN/m). Axial momentum accumulation begins decreasing at 22% chord, indicating that net axial forces become upstream-directed and leakage-induced backflow begins dominating the tip flow field. [Figure 9: see original paper] reveals that plasma actuation at different positions has minimal effect on axial momentum accumulation, preventing clear identification of its influence on tip flow axial momentum.

Control volume axial momentum change reflects the magnitude and direction of net axial forces. Positive axial momentum change indicates downstream-directed net force with mainstream-dominated tip flow, while negative change indicates upstream-directed force with leakage backflow dominance. The magnitude directly reflects the net force magnitude. Unlike circumferential groove casing treatments, plasma actuation's limited influence range means its effect on tip flow axial momentum cannot be represented by control volume forces alone. Therefore, axial momentum flux through surface A1 of each control volume was analyzed to assess plasma actuation effects.

[Figure 10: see original paper] shows blade tip flow field axial momentum changes with plasma actuation at different positions (single actuator body force = 50 mN/m). Despite minimal effects on control volume forces, plasma actuation significantly altered tip flow axial momentum. All positions increased tip flow axial momentum, with Dis = 0% chord (at leading edge) having the smallest effect, Dis = 20% chord (near mainstream/leakage interface) providing the greatest increase, and Dis = 40% chord (within leakage region) showing slightly stronger effects than Dis = 0% chord. This explains why Dis = 40% chord actuation reduced tip blockage more than Dis = 0% chord in [Figure 6: see original paper].

2 Plasma Flow Control for Axial Compressor Stall

2.1 Numerical Simulation

Previous experimental and numerical studies have shown that plasma actuation on the rotor tip casing can effectively suppress compressor stall by influencing rotor tip flow. Saddoughi et al. [17] experimentally demonstrated that plasma actuation could extend transonic compressor stall margin, with improvement primarily attributed to effects on rotor tip leakage flow unsteady characteristics.

Synthesizing prior research, plasma actuation’ s key to compressor stall suppression lies in controlling tip leakage flow. The flow control laws and mechanisms obtained in Section 1 should be analogously applicable to compressor stall plasma flow control. To verify the correlation between plasma actuation’ s performance improvement capability and its influence on rotor tip leakage flow, numerical simulation of axial compressor stall plasma flow control was conducted.

2.1.1 Research Object and Numerical Simulation Method This study used the 1.5-stage low-speed large-scale compressor test rig at Beihang University as the research object, with detailed parameters provided in . Simulations were performed using Ansys CFX with the k- two-equation eddy viscosity model. Computational domains included two guide vane passages, one rotor passage, and one stator passage with 1.35 million, 2.88 million, and 0.9 million grid cells respectively. Local refinement was applied at rotor tip casing plasma actuation positions and near-wall regions to ensure y+ < 2.

The computational domain inlet was located 3 tip chord lengths upstream of the guide vane, with total pressure distribution specified based on experimental measurements (Figure 11: see original paper). The outlet was positioned 5 tip chord lengths downstream of the stator, with mass flow specified. Solid walls were modeled as adiabatic no-slip surfaces. Plasma actuation simulation methods remained consistent with Section 1.

2.1.2 Plasma Actuation Layout [Figure 12: see original paper] illustrates the plasma actuation layout on the rotor tip. Similar to Section 1, Dis is defined as the distance between the upper/lower electrode interface and the rotor tip leading edge. For installation angle actuation layouts, Dis represents the distance between the electrode interface and the line connecting rotor tip leading and trailing edges.

[Figure 13: see original paper] shows the near-wall jet velocity distribution induced by a single plasma actuator in quiescent air under different actuation strengths. To ensure noticeable effects on compressor stall, the induced body force exceeded that in Section 1’ s [Figure 4: see original paper]. When plasma actuation induced a body force of 293 mN/m, the maximum induced velocity reached 11 m/s, achievable in real experiments using multiple actuators [43].

2.1.3 Plasma Flow Control Effectiveness The flow coefficient is defined as:

$$F_c = \frac{C_a}{U_m}$$

The compressor stage total-to-static pressure rise coefficient is:

$$\psi = \frac{p_3 - p_{1t}}{\rho U_m^2/2}$$

The compressor stage static pressure rise coefficient is:

$$\phi = \frac{p_3 - p_1}{\rho U_m^2/2}$$

The rotor static pressure rise coefficient is:

$$\phi_R = \frac{p_2 - p_1}{\rho U_m^2/2}$$

The stator static pressure rise coefficient is:

$$\phi_S = \frac{p_3 - p_2}{\rho U_m^2/2}$$

where C_a is inlet axial velocity, U_m is rotor mid-span tangential velocity, p_1, p_2, and p_3 are static pressures upstream of rotor, between rotor and stator, and downstream of stator respectively, and p_{1t} is inlet total pressure.

Research [44] indicates that compressor stall characteristics are closely related to the peak of the total-to-static pressure rise characteristic curve. Therefore, compressor stall analysis in this study employs total-to-static pressure rise characteristics.

[Figure 14: see original paper] shows the effect of different actuator positions on compressor total-to-static pressure rise characteristics for a body force of 293 mN/m. Plasma actuation increases the total-to-static pressure rise coefficient and extends the stable operating range. Dis = -5% rotor tip chord actuation provides the greatest increase in stable operating range and pressure rise coefficient. Performance improvement capability gradually weakens as actuators move further upstream. When actuators move downstream of the rotor tip leading edge (Dis = 5% and 10% chord), performance improvement capability decreases rapidly. Thus, actuation downstream of the rotor tip leading edge is significantly less effective than upstream actuation.

In real engines, comprehensive stall margin is typically determined based on flow coefficient and total pressure ratio differences between near-stall points and the operating line at a given speed [1]. For the 1.5-stage compressor studied here without an operating line and with small total pressure rise, stall margin is defined as the flow coefficient difference between near-stall and design points. Stall margin improvement (SMI) with plasma actuation is defined as:

$$\mathrm{SMI} = \frac{\Delta F_{ca} - \Delta F_{cb}}{\Delta F_{cb}} \times 100\%$$

where ΔF_{cb} and ΔF_{ca} are flow coefficient differences between near-stall and design points under baseline and actuated conditions, respectively.

To comprehensively evaluate flow control effectiveness, following Suder et al. [45], the change in near-stall point flow coefficient (ΔF_{cs}) is defined as:

$$\Delta F_{cs} = \frac{F_{csb} - F_{csa}}{F_{csb}} \times 100\%$$

where F_{csb} and F_{csa} are near-stall point flow coefficients under baseline and actuated conditions.

To evaluate effects on compressor pressure rise capability, the change in maximum static pressure rise coefficient ($\Delta \phi_m$) is defined as:

$$\Delta \phi_m = \frac{\phi_{ma} - \phi_{mb}}{\phi_{mb}} \times 100\%$$

where ϕ_{mb} and ϕ_{ma} are maximum static pressure rise coefficients under baseline and actuated conditions.

[Figure 15: see original paper] shows the effects of different actuator positions on compressor performance for a body force of 293 mN/m. All positions reduce near-stall flow coefficient, increase stall margin, and improve pressure rise capability. Dis = -5% rotor tip chord actuation provides the most significant improvement: 127.46% increase in stall margin, 8.73% reduction in near-stall flow coefficient, and 3.32% increase in maximum static pressure rise coefficient. Performance improvement gradually weakens as actuators move upstream, with Dis = -25% chord providing 87.47% stall margin increase, 5.99% flow coefficient reduction, and 2.87% pressure rise increase. Downstream actuation (Dis = 5% and 10% chord) shows rapid performance degradation, with stall margin improvements only 28.6% and 42.7% of the Dis = -25% case, respectively. These quantitative results further demonstrate that downstream actuation is significantly less effective than upstream actuation.

[Figure 16: see original paper] shows rotor tip leakage flow patterns and pitchwise-averaged casing axial shear stress distribution at near-stall conditions. The mainstream/leakage flow interface is essentially parallel to the rotor tip leading edge line. The average interface axial position is at 2.5% rotor tip chord. Therefore, Dis = -5% chord actuation is located 2.5% chord upstream of the interface. Actuation near the upstream region of the interface provides the strongest leakage suppression, making Dis = -5% chord most effective for performance improvement. Combined with Vo et al. [9], this confirms that stall control 关键在于 tip leakage flow suppression.

For Dis = 5% and 10% chord actuation located downstream of the rotor tip leading edge, the induced body force acts directly within the leakage-induced backflow region, causing additional flow mixing and increased blockage. This explains their weaker performance improvement compared to upstream actuation. The near-stall leakage vortex development determines the interface position, with the vortex containing stronger shear flow than leakage flow in the blade rear section. Dis = 10% chord actuation, being farther from the leading edge and leakage vortex than Dis = 5% chord, causes weaker additional mixing, resulting in better performance improvement than Dis = 5% chord.

2.1.4 Plasma Actuation Effects on Rotor Tip Axial Momentum [Figure 17: see original paper] shows the influence of different actuator positions on rotor tip flow field axial momentum (body force = 293 mN/m). Downstream actuation (Dis = 5% chord) shows minimal increase in rotor tip axial momentum, indicating weak leakage suppression capability. In contrast, Dis = -5% and -15% chord actuation produce comparable effects, with Dis = -5% chord providing slightly higher axial momentum increase beyond 30% chord.

The maximum point on axial momentum variation curves marks the boundary between mainstream-dominated and leakage-dominated regions. Beyond this maximum, axial momentum decreases under leakage-induced backflow. A maximum point farther from the leading edge indicates less developed leakage-dominated region near the leading edge and higher quality rotor tip flow field. Dis = -5% chord actuation produces a maximum point significantly farther from the leading edge than Dis = -15% chord, explaining its superior performance improvement.

In summary, plasma actuation interaction with axial compressor rotor tip leakage flow is more complex than in cascade environments. Optimal actuation layout should consider both the ability to increase tip flow axial momentum and its influence on the mainstream/leakage flow dominance boundary, similar to the "bell-shaped curve" findings for circumferential groove casing treatments [42].

2.2 Experimental Study

Despite nearly a decade of development, systematic experimental studies on compressor stall plasma flow control remain lacking, limiting deeper understanding of relevant laws and mechanisms. This section presents experimental research on plasma actuation for stall suppression using a vertical compressor test facility designed by the authors.

2.2.1 Research Object and Test Facility Structure The compressor test facility approximates multi-stage compressor environments. Unlike conventional single-stage rigs, it features five blade rows: inlet guide vane, stator, rotor, stator, and exit guide vane, with the inlet guide vane simulating rotor exit flow conditions. This study focuses on plasma actuation effects on a single compressor stage comprising the rotor and second stator, with detailed parameters provided in .

[Figure 18: see original paper] shows the overall test facility structure. The plasma power supply, electrical measurement equipment, and actuators are identical to those in Chapter 2. The facility includes inlet, test, and support sections, with the drive motor and throttle valve located within the support structure. The compressor design speed is 2400 RPM; measurements were conducted at 1600 RPM, 2000 RPM, and 2400 RPM.

Since no flow straightening screens were installed in the inlet section, inlet total pressure p_0 used ambient atmospheric pressure. Inlet axial velocity was obtained by measuring static pressure p_s upstream of the guide vane. Compressor stage static pressure rise characteristics, rotor static pressure rise characteristics, and stator static pressure rise characteristics were obtained by measuring static pressures p_1 upstream of the rotor, p_2 upstream of the second stator, and p_3 downstream of the second stator.

2.2.2 Plasma Actuation Layout [Figure 19: see original paper] shows the plasma actuator schematic. Two actuator groups (Actu1 and Actu2) were used to generate sufficient body force. Four identical actuators were assembled and embedded in a casing with installation grooves, producing circumferentially uniform body force distribution when high voltage was applied to the electrodes, subjecting the rotor tip region to constant axial body force during operation.

[Figure 20: see original paper] shows actuator installation and discharge characteristics. A key advancement over previous studies is the use of non-metallic materials for both rotor blades and tip casing, effectively preventing creeping discharge between plasma actuators and surrounding metal components.

2.2.3 Plasma Actuation Flow Control Effectiveness For low-speed single-stage axial compressors without an operating line and with small total pressure rise, stall margin was defined differently than in numerical studies. [Figure 21: see original paper] shows static pressure rise characteristics at different speeds. Curve L_{sc} represents the stall boundary, while L_m connects maximum pressure rise points. Near-stall flow coefficients show little variation with speed, but the distance between stall boundary and maximum pressure rise point differs significantly. Lower compressor speeds bring the stall boundary closer to the maximum pressure rise point. Since actual operating points should approach the maximum pressure rise point for sufficient pressure rise capability, this distance reflects stable operating range. To compare flow control effectiveness across speeds, stall margin (SM) was defined as the flow coefficient difference between near-stall and maximum pressure rise points, with stall margin improvement (SMI) calculated using equation (13).

[Figure 22: see original paper] compares static pressure rise characteristics with and without plasma actuation at 15 kV excitation voltage. At 1600 RPM and 2000 RPM, plasma actuation increases stall margin while enhancing static pressure rise coefficient, primarily because actuation near the rotor tip leading edge effectively suppresses tip leakage flow. At large flow coefficients, actuation effects on static pressure rise are relatively small, but as flow coefficient decreases, the increase in static pressure rise coefficient becomes more pronounced. At 2400 RPM, plasma actuation does not significantly change static pressure rise coefficient but still notably improves stall margin, indicating that stall suppression capability is not directly correlated with static pressure rise effects. This experimental phenomenon aligns with GE' s transonic compressor plasma flow control results [17], which showed that plasma actuation could extend stable operating range without altering large-flow-point characteristics.

quantifies plasma actuation effects on compressor performance at 15 kV. The $\Delta\phi_{\text{aver}}$ values show no significant static pressure rise change at 2400 RPM, but increases at 1600 RPM and 2000 RPM, with greater enhancement at 1600 RPM. Comparing SMI values across speeds reveals strongest stall suppression at 1600 RPM, gradually weakening with increasing speed. SMI decreases by 30.17% when speed increases from 1600 RPM to 2000 RPM, but only 7.81% from 2000 RPM to 2400 RPM. The ΔF_{cs} values show similar trends, with 1.6% near-stall flow coefficient change at 1600 RPM, gradually decreasing with speed but at a slowing rate.

3 Plasma Flow Control of Three-Dimensional Corner Separation in High-Speed Compressors

The authors' group previously studied plasma aerodynamic actuation for low-speed axial compressor cascade three-dimensional corner separation. This section investigates high-speed compressor cascade corner separation control through numerical simulation to obtain control laws and mechanisms.

3.1 Research Object

The NACA65-K48 high-speed compressor cascade was selected as the research object. Based on real engine high-pressure compressor stator inlet conditions, "high-speed" here refers to high subsonic conditions with inlet Mach number fixed at 0.7. The cascade model is shown in [Figure 23: see original paper], with detailed parameters in .

3.2 Plasma Actuation Layout and Numerical Simulation Method

To effectively control high-speed compressor cascade three-dimensional corner separation, plasma actuation was applied on both endwall and suction surface as shown in [Figure 24: see original paper]. Endwall actuation reduces low-energy fluid accumulation in the endwall/suction surface corner region and suppresses passage vortex development, while suction surface actuation reduces mainstream effects of three-dimensional corner separation and decreases wall vortex intensity.

Six plasma actuator groups (SA1-SA6) were arranged on the suction surface (Figure 24: see original paper), with SA1 positioned 15% chord from the blade leading edge and subsequent actuators spaced 15% chord apart along the spanwise direction. Six actuator groups (EA1-EA6) were arranged on the endwall (Figure 24: see original paper), with EA1 at 15% chord from the leading edge and subsequent actuators spaced 15% chord apart along the local suction surface normal direction.

[Figure 25: see original paper] shows the near-wall jet velocity distribution induced by six actuator groups in quiescent air under different strengths, with body force values representing those generated by a single actuator. In transonic compressor plasma flow control experiments, GE [17] used multiple actuators producing maximum induced velocities around 30 m/s. For the present layout, when a single actuator generates 837 mN/m body force, six actuators induce maximum near-wall jet velocity of approximately 31 m/s, comparable to GE' s configuration.

[Figure 26: see original paper] shows the computational grid for high-speed compressor cascade plasma flow control simulations, using an H-O-H topology. To accurately simulate plasma effects, local refinement was applied at actuator positions in [Figure 24: see original paper], resulting in 2.8 million total grid cells. The k- eddy viscosity model was employed. Suzen et al.' s phenomenological model [39] was used to solve for plasma-induced body forces, which were applied as boundary conditions at actuator locations to control flow separation.

3.3 Suction Surface Actuation Effectiveness

The section-averaged static pressure rise coefficient is defined as:

$$C_{ps} = \frac{\int_S C_p \, dS}{S}$$

where S is the selected cross-sectional area and C_p is the static pressure rise coefficient. All subsequent calculations for C_{ps}, ω_s, and A_b at the high-speed compressor cascade outlet were performed at the 60% chord downstream section.

[Figure 27: see original paper] shows cascade outlet plane-averaged flow parameters versus incidence angle with suction surface actuation from Figure 24: see original paper. [Figure 28: see original paper] presents relative change rates of outlet plane-averaged flow parameters under different incidence angles (single actuator body force = 837 mN/m).

Absolute total pressure loss reduction is most significant near design incidence, weakening at large negative and positive incidence angles. According to [Figure 28: see original paper], suction surface actuation reduces cascade passage loss by

10.1% at 1° incidence, with relative reduction decreasing as incidence increases or decreases. At -4° incidence, loss reduction is 3.3%; at 10° incidence, 4.8%. Overall, suction surface actuation is more effective for positive incidence than negative incidence conditions.

Absolute static pressure rise coefficient increases with suction surface actuation, with greater enhancement at positive incidence. [Figure 28: see original paper] shows relative static pressure rise coefficient increases of approximately 3% across all incidence angles.

Suction surface actuation reduces cascade passage blockage, but with relatively small effect. Maximum blockage coefficient reduction is 2.3% at 0° incidence, decreasing to 1% at 10° incidence as three-dimensional corner separation strengthens. At -4° incidence, although absolute blockage change is small, the relative change reaches 2% due to lower baseline blockage. Blockage suppression weakens as incidence deviates from 0° in either direction. At 3° incidence, blockage reduction is 2%; at -3° incidence, only 1.3%. Suction surface actuation is more effective for positive incidence blockage suppression.

3.4 Endwall Actuation Effectiveness

[Figure 29: see original paper] shows cascade outlet plane-averaged flow parameters versus incidence angle with endwall actuation from Figure 24: see original paper. [Figure 30: see original paper] presents relative change rates (single actuator body force = 837 mN/m).

Absolute total pressure loss reduction with endwall actuation is more pronounced at positive incidence than negative incidence. At negative incidence, pressure surface separation exists and endwall actuation cannot effectively reduce mid-span profile losses, resulting in smaller loss changes than suction surface actuation. At -4° incidence, endwall actuation reduces loss by only 0.5%. As incidence increases, endwall/suction surface corner separation strengthens, enabling more effective loss reduction. Maximum loss reduction of 5.7% occurs at 7° incidence, though lower than suction surface actuation’ s optimum. Beyond 8° incidence, corner stall occurs and the applied actuation intensity becomes insufficient, reducing effectiveness to 3.3% loss reduction at 10° incidence.

Absolute static pressure rise coefficient increases with endwall actuation, more significantly at positive incidence. According to [Figure 30: see original paper], maximum pressure rise capability enhancement of 4.2% occurs at 1° incidence, exceeding suction surface actuation effectiveness. Relative pressure rise increase gradually decreases with incidence, reaching 2.8% at 10° incidence. At negative incidence, despite small absolute changes, relative changes remain large (4% at -4° incidence) due to low baseline pressure rise.

Comparing Figure 27: see original paper and Figure 29: see original paper reveals that endwall actuation suppresses passage blockage much more effectively than suction surface actuation. By suppressing three-dimensional corner separation (the primary blockage source), endwall actuation more effectively reduces flow blockage. Absolute blockage reduction is strongest for -3° to 7° incidence range. Maximum blockage coefficient reduction is 9.4% at 0° incidence, decreasing to 1.8% at 10° incidence as separation intensifies. At 4° incidence, blockage reduction is 5.8%; at -4° incidence, 4.5%. Endwall actuation is more effective for positive incidence blockage suppression.

Overall, different optimal actuation layouts exist for suppressing flow losses versus blockage in high-speed compressor cascades. Suction surface actuation more effectively reduces flow losses, while endwall actuation more effectively reduces blockage and enhances pressure rise capability. Both actuation types are more effective at positive incidence than negative incidence, though limited influence range reduces effectiveness for strong three-dimensional corner separation at large positive incidence.

4 Plasma-Actuated Compressor

In traditional compressor design and research, flow control is primarily treated as an auxiliary means, greatly limiting its effectiveness. The development of aspirated compressors and coupled optimization studies of compressor geometry and flow control [46] demonstrate that integrating flow control into aerodynamic design can release many design constraints, making the previously impossible achievable.

The key to flow-control-integrated compressor design lies in advanced flow control technology and its high-degree coupling with compressor design. The NATO "More Intelligent Gas Turbine Engines"research group (comprising NASA, MTU, GE, Rolls-Royce, etc.) concluded that efficient compressor active flow control actuation must meet: response time < 4 ms, excitation bandwidth covering 200-300 Hz (rotational frequency), 500 Hz-2 kHz (large-scale separation frequency), 5-20 kHz (blade passing frequency), and 50-100 kHz (vortex shedding frequency), high actuation intensity, and good robustness [47]. Reference [48] suggests generating spatially distributed excitation of specific waveforms and frequencies to resonate with tip leakage vortex cores for dissipation and stability enhancement. Plasma actuation shows promise as an alternative to rotor tip injection.

Based on compressor plasma flow control research, the concept of plasma-actuated compressors is proposed, incorporating plasma actuation as an independent design variable in compressor design, significantly broadening design space while increasing complexity. The main technical features include coupling optimization of plasma actuation and geometric shaping to achieve efficient, rapid, wide-range modulation of boundary layers, separated flows, and leakage flows, expanding design parameter space and substantially improving performance and efficiency.

Primary technical approaches include: 1. Coupled optimization of plasma actuation and rotor tip geometry to control tip leakage flow and expand stability margin. Tip leakage flow is a major stall inception factor. Future focus will be multi-stage compressor tip leakage control. 2. Coupled optimization of plasma actuation and blade suction surface geometry to control boundary layer transition and improve compressor efficiency. Suction surface transition control can significantly improve efficiency at conventional loading, while pressure surface control may significantly impact high-load conditions. 3. Coupled optimization of plasma actuation and blade suction surface geometry to control leading edge disturbance flows, expanding usable incidence range and stability margin. 4. Coupled optimization of plasma actuation and blade suction surface geometry to modulate blade wakes, simplifying guide vane design or modulating wake frequencies to alleviate high-cycle fatigue. 5. Coupled optimization of plasma actuation and blade/endwall geometry to control endwall three-dimensional flows and improve compressor performance. Three-dimensional corner separation is a critical weak region significantly affecting performance and robustness. Plasma actuation can improve design robustness, reduce risk, and lower manufacturing and maintenance costs beyond geometric optimization.

The scientific connotation of plasma-actuated compressors 主要体现在: 1. At the overall design exploration level, proposing new inter-stage loading distribution, rotor/stator loading allocation, and plasma-actuated airfoil concepts for future high-efficiency, wide-margin axial compressors, guided by plasma actuation flow control potential. 2. At the coupled optimization exploration level, establishing description and optimization methods for plasma actuation-geometry coupling using surrogate models and plasma phenomenological models. 3. At the novel high-intensity plasma actuation exploration level, developing methods to increase induced body force and rapid heating intensity based on overall design and optimization objectives. 4. At the mechanism exploration level, revealing mechanisms of coupled optimization for controlling leakage flow, leading edge high-curvature flow, boundary layer transition, wake flow, and endwall corner separation.

5 Summary and Outlook

1. Increasing tip flow axial momentum is key to plasma actuation suppression of leakage flow. Actuation located near the upstream region of the mainstream/leakage flow interface maximizes axial momentum increase, providing strongest suppression.
2. Numerical results indicate that plasma actuation improves axial compressor performance primarily by increasing rotor tip axial momentum to suppress tip leakage flow development. For stall suppression, optimal actuation layout should consider both momentum increase capability and influence on the mainstream/leakage flow dominance boundary.
3. Experimental results show that for the studied actuation layout, plasma actuation can improve both stall margin and static pressure rise coefficient, but these improvements are not directly correlated. Effects on both parameters decrease with increasing speed but increase with decreasing

flow coefficient.

4. Different optimal plasma actuation layouts exist for suppressing flow losses versus blockage in high-speed compressor cascades. Endwall actuation is less effective than suction surface actuation for loss reduction but more effective for pressure rise and blockage reduction. Both actuation types are more effective at positive than negative incidence, though limited influence range reduces effectiveness for strong three-dimensional corner separation at large positive incidence.

By suppressing tip leakage flow, plasma actuation can improve compressor stall margin, with optimal effectiveness depending on increasing tip flow axial momentum. To enhance stall suppression capability, actuation layout should be optimized and high-performance actuators employed to maximize rotor tip axial momentum.

Experimental validation confirms plasma actuation' s ability to improve compressor stall margin. Discrepancies exist between numerical and experimental results, necessitating development of appropriate experimental platforms for systematic experimental research to further advance application.

Both endwall and suction surface plasma actuation can effectively suppress high-speed compressor cascade three-dimensional corner separation, with effectiveness strongly dependent on actuation layout. Future research should optimize layouts based on flow control mechanism analysis to improve efficiency and achieve effective suppression with relatively small energy input.

Based on mechanistic understanding of compressor plasma flow control, coupling plasma actuation layout with aerodynamic profile design to develop plasma-actuated compressors promises to significantly expand design space and improve performance. This represents an important future direction requiring in-depth investigation of numerous scientific questions.

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