Effect of Local Tip Forward Sweep on the Aerodynamic Performance of Transonic Cantilever Stators (Postprint)

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Abstract

The effects of local tip forward sweep on the aerodynamic performance of transonic cantilever stators were investigated. On the one hand, local tip forward sweep can reduce the peak Mach number in the transonic region on the suction surface at the hub end of the cantilever stator, thereby decreasing shock wave losses; on the other hand, it can reduce the peak loading at the hub end of the cantilever stator, redistributing the loading along the chordwise direction and reducing leakage losses. Furthermore, applying this local tip forward sweep technology to the transonic cantilever stator in an industrial multi-stage axial compressor increased the adiabatic efficiency of the multi-stage compressor by nearly 0.85% while maintaining the total pressure ratio and stable operating range.

Full Text

Study on the Effect of Forward End Sweep on the Aerodynamic Performance of Transonic Cantilevered Stators

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Abstract

This paper investigates the effect of forward end sweep on the aerodynamic performance of cantilevered stators. On one hand, forward end sweep can reduce the peak Mach number in the transonic region on the hub suction surface of cantilevered stators, thereby decreasing shock losses. On the other hand, it can reduce the peak loading at the hub end, redistribute the loading along the chordwise direction, and decrease leakage losses. Furthermore, this technology was applied to the transonic cantilevered stators in an industrial multistage axial-flow compressor, achieving nearly 0.85% improvement in adiabatic efficiency while maintaining the total pressure ratio and stable operating range.

Keywords: forward end sweep; cantilevered stator; shock loss; leakage loss; multistage axial compressor

1. Introduction

In recent years, to further improve the performance of turbomachinery compression systems, compressor design loads have been progressively increased toward their limits, resulting in increasingly complex internal flow phenomena. As critical components in multistage axial compressors, stators operate under strong adverse pressure gradients. The quality of their internal flow not only determines the magnitude of flow losses within the stator itself but also significantly influences the flow field in downstream rotor stages. Therefore, rationally optimizing the internal flow of stators and comprehensively improving their aerodynamic performance is of great significance for enhancing the overall performance of multistage compressors.

Over the past three decades, three-dimensional (3-D) blade shaping techniques have been widely applied in the aerodynamic design of shrouded stators [1,2]. Researchers have investigated the effects of bow and sweep design on the aerodynamic performance of shrouded stators through numerical and experimental studies [3-6]. For bow design, positive bow at the endwalls can reduce endwall losses, albeit with increased losses in the mid-span region, resulting in an overall reduction in total aerodynamic losses for the stator. Regarding sweep design, Friedrichs et al. [7] experimentally demonstrated that stator blades with leading-edge sweep exhibited improved aerodynamic performance in the hub region compared to conventional stators.

Concurrently, driven by increasing demands for compressor weight reduction, the integrally bladed rotor and cantilevered stator configuration—unlike shrouded stators—has been widely adopted in small aero-engine compressors. As compressor loads continue to rise, flow phenomena such as transonic regions, shock waves, and hub leakage flows within cantilevered stator passages have become significant sources of aerodynamic loss that severely impact overall performance.

The internal flow field of high-load transonic cantilevered stators differs substantially from that of conventional shrouded stators, with shock losses and leakage losses emerging as non-negligible factors contributing to aerodynamic losses. To address this issue, Lange et al. [8] designed bowed cantilevered stators to reduce aerodynamic losses caused by leakage flows and validated the approach using a 4-stage low-speed axial compressor. Domestically, Luo et al. [9] and Wang et al. [10] also conducted detailed investigations into the effects of bow design on the flow field within cantilevered stators.

Currently, published research on cantilevered stators has primarily focused on the influence of bow design on internal flow and aerodynamic performance. However, the successful application of sweep design for controlling shock losses in transonic rotors [11,12] provides valuable references for its implementation in transonic cantilevered stators. This paper attempts to employ local end forward sweep design near the hub end of transonic cantilevered stators and investigates its effects on shock losses, leakage losses, and overall aerodynamic performance through numerical simulations.

1.1 Prototype Cantilevered Stator

The research object in this study is illustrated in Figure 1 [Figure 1: see original paper], where S1 denotes the cantilevered stator under investigation. In the hub region of the cantilevered stator, a clearance gap exists between the stator blade and the hub wall. To simulate realistic inlet conditions for the cantilevered stator, the computational model also includes the upstream inlet guide vane and rotor blade. The geometric parameters of this 1.5-stage compressor and the cantilevered stator are presented in Table 1 .

1.2 End-Swept Cantilevered Stator

In this study, sweep is defined as the chordwise movement of airfoil sections. When an airfoil section moves upstream along the chordwise direction, it is defined as forward sweep; conversely, downstream movement is defined as backward sweep. Figure 2 [Figure 2: see original paper] presents a schematic diagram illustrating the generation of an end forward swept stator from the baseline design. The end forward swept stator is obtained by modifying the curvature of the baseline stator' s stacking line, with seven control points uniformly distributed along the baseline stacking line. Movement of each control point along the chordwise direction of the airfoil section produces the sweep effect.

To ensure that the sweep design produces pronounced aerodynamic effects in the transonic cantilevered stator and to facilitate investigation of its influence on the internal flow, an optimization design approach was employed for the local end forward sweep implementation. This optimization aims to enhance the sweep effect, enabling clearer identification of the mechanisms through which local end forward sweep design influences the internal flow and aerodynamic losses in transonic cantilevered stators.

2. Numerical Methods

The numerical calculations in this study were performed using the commercial CFD software FINE/TURBO from NUMECA. The Navier-Stokes equations were solved using the FINE module, with spatial discretization achieved through a central difference scheme and time marching accomplished via fourth-order

Runge-Kutta iterative solution. Multigrid techniques and local time stepping were employed during the computation to accelerate convergence. The Spalart-Allmaras turbulence model was adopted, with ideal gas selected as the working fluid.

The simulations were conducted on a single passage basis. The compressor inlet was prescribed with standard atmospheric conditions (total pressure 101325 Pa, total temperature 288.15 K) and axial inflow direction, while static pressure conditions were specified at the outlet boundary. All solid walls in the computational model were treated with adiabatic no-slip conditions. The grid topology in the blade passage utilized an O4H structure, with O-type grids surrounding the blade and H-type grids in other regions, as shown in Figure 3 [Figure 3: see original paper]. A butterfly grid structure was employed in the tip clearance region of the cantilevered stator to improve orthogonality. To ensure accurate simulation of the flow field within the clearance gap, approximately 17 grid nodes were distributed in the radial direction inside the gap. Additionally, appropriate refinement was applied to wall regions throughout the computational domain to ensure that the first grid node satisfied $y+ < 5$ (as shown in Figure 4 [Figure 4: see original paper]).

To validate the reliability of the numerical methods and tools employed in this study, experimental results from another 1.5-stage axial compressor were used for verification, as shown in Figure 5 [Figure 5: see original paper], since experimental data for the specific cantilevered stator under investigation were unavailable. This 1.5-stage axial compressor represents the front 1.5 stages of a 3.5-stage axial compressor test rig, with experimental data extracted from the full 3.5-stage facility [13]. In the actual computations, the radial distribution of static pressure at the S1 stator exit obtained from experiments was prescribed as the outlet boundary condition for the 1.5-stage axial compressor. The comparison between numerical results and experimental data is presented in Figure 6 [Figure 6: see original paper], demonstrating good agreement and confirming the reliability of the adopted numerical methods and tools.

3.1 Effect of Local End Forward Sweep on Shock Loss

Figure 7 [Figure 7: see original paper] presents Mach number contours near the suction surface for both the baseline and locally end-swept cantilevered stators. In the baseline configuration, a transonic region is clearly observable in the hub corner of the suction surface (region A). Upon application of local end forward sweep to the baseline stator, the area of the transonic region in the hub corner of the suction surface is reduced. Simultaneously, the peak Mach number on the suction surface is significantly decreased (from 1.33 in the baseline to 1.21 in the modified design), resulting in corresponding reductions in shock losses within the stator flow.

These results demonstrate that local end forward sweep can reduce shock losses by effectively decreasing both the area of the transonic region on the suction surface of transonic cantilevered stators and the associated peak Mach number, thereby improving aerodynamic performance.

3.2 Effect of Local End Forward Sweep on Leakage Loss

Unlike shrouded stators, cantilevered stators feature a clearance gap between the blade and hub wall, making leakage flow near the hub wall another major source of total aerodynamic loss. Figure 8 [Figure 8: see original paper] compares the load distributions along the chordwise direction near the hub region for both baseline and locally end forward swept cantilevered stators. The load coefficient is defined as:

$$\text{Load Coefficient} = \frac{P_{ps} - P_{ss}}{P_{in}}$$

where P_{ps} and P_{ss} represent the pressures on the blade pressure and suction surfaces, respectively, and P_{in} denotes the stator inlet total pressure. The comparison reveals that local end forward sweep redistributes the loading near the hub region and reduces the peak loading of the cantilevered stator in this area.

Figure 9 [Figure 9: see original paper] presents entropy contours on blade passage cross-sections for both configurations. The results show that by reducing the peak loading near the hub region, local end forward sweep weakens the leakage flow, which not only decreases leakage losses but also alleviates blockage near the hub wall.

In summary, local end sweep can reduce leakage losses by decreasing the peak loading near the hub region of cantilevered stators, thereby weakening leakage flow and improving aerodynamic performance.

3.3 Application of Local End Forward Sweep in Multistage Axial Compressors

Given that local end forward sweep effectively reduces both shock losses and leakage losses at the hub end of cantilevered stators and contributes to improved overall aerodynamic performance, this technology was applied to the aerodynamic design of transonic cantilevered stators in an industrial multistage axial compressor with the objective of enhancing the adiabatic efficiency of the entire compressor.

Specifically, local end forward sweep was applied to the first four transonic cantilevered stator rows (S1, S2, S3, and S4) in this multistage axial compressor. The baseline and modified stators are illustrated in Figure 10 [Figure 10: see original paper]. Figure 11 [Figure 11: see original paper] presents a comparison of aerodynamic losses between the baseline and forward end swept cantilevered stators, where aerodynamic loss is defined as:

$$\text{Aerodynamic Loss} = \frac{P_{t,in} - P_{t,out}}{P_{in}}$$

where $P_{t,in}$ and $P_{t,out}$ represent the total pressures at the stator inlet and outlet, respectively, and P_{in} denotes the inlet static pressure. The comparison demonstrates significant reductions in aerodynamic losses for the first four stator rows after implementing local end forward sweep, confirming the effectiveness of this technology in reducing aerodynamic losses in transonic cantilevered stators.

Figure 12 [Figure 12: see original paper] compares the aerodynamic performance of the baseline compressor with that of the modified compressor incorporating local end forward sweep in the stators. Throughout the operating range, the modified compressor exhibits substantially improved aerodynamic performance, with the adiabatic efficiency increased by nearly 0.85%. Moreover, at equivalent total pressure ratios, the modified compressor consistently demonstrates higher adiabatic efficiency than the baseline design. These results indicate that local end forward sweep technology can effectively reduce aerodynamic losses in transonic cantilevered stators, significantly improve their aerodynamic performance, and consequently enhance the overall performance of multistage axial compressors.

4. Conclusions

This paper investigates transonic cantilevered stators with local end forward sweep design applied near the hub end to explore its effects on shock losses and leakage losses. The technology was further applied to the aerodynamic design of transonic cantilevered stators in a multistage axial compressor, leading to the following conclusions:

1. Local end forward sweep can reduce shock losses by effectively decreasing the area of transonic regions on the suction surface of transonic cantilevered stators and reducing the corresponding peak Mach number, thereby improving aerodynamic performance.

2. Local end forward sweep can effectively reduce the peak loading near the hub region of cantilevered stators, alter the load distribution, weaken leakage flow, and consequently reduce leakage losses, leading to improved aerodynamic performance.

3. Application of local end forward sweep technology to the aerodynamic design of transonic cantilevered stators in a multistage axial compressor significantly reduced aerodynamic losses in the transonic cantilevered stators and substantially improved the overall aerodynamic performance of the modified multistage axial compressor, demonstrating the significant potential of this technology for enhancing multistage axial compressor performance.

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Note: Figure translations are in progress. See original paper for figures.