Experimental Study on Circumferential Propagation Characteristics of Tip Clearance Leakage Flow in Axial Compressors (Postprint)

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Abstract

On a single-rotor low-speed axial compressor, taking the unsteadiness of tip clearance leakage flow as the entry point, the frequency modulation characteristics of unsteady fluctuation features in the tip region along the blade chord were analyzed through experimental measurements of unsteady wall pressure along the chordwise and circumferential directions. The propagation characteristics of the dominant unsteady fluctuations of tip clearance leakage flow along the circumferential direction were investigated, and the evolution law from tip clearance leakage flow unsteadiness fluctuations to stall precursor signal generation was further analyzed. Experimental results demonstrate that the tip region flow field dominated by unsteady fluctuations of tip clearance leakage flow exhibits a gradually increasing circumferential propagation speed during the compressor throttling process until the emergence of stall precursors. From this, it can be concluded that tip clearance leakage flow unsteadiness constitutes the flow field basis for stall precursor signal analysis and prediction, providing guidance for clarifying and understanding the unified fluid mechanics mechanism underlying the distinct flow characteristics ranging from tip clearance leakage flow unsteadiness to stall precursors and eventually to stall.

Full Text

Preamble

Experimental Investigation on Circumferential Propagation of Tip Leakage Flow in Axial Compressor

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Abstract: This paper investigates the circumferential propagation of disturbances dominated by the unsteadiness of tip leakage flow based on unsteady measurements along the blade chord and circumferential direction. The evolution from tip leakage flow unsteadiness to stall inception during compressor throttling is further analyzed. Experimental results indicate that the circumferential propagation speed of unsteady tip leakage flow increases during the throttling process, but only after the emergence of tip leakage flow unsteadiness. This demonstrates that tip leakage flow unsteadiness provides the physical basis for analyzing and predicting stall inception, offering guidance toward understanding the unified fluid mechanics mechanism linking the distinct flow characteristics of unsteady tip leakage flow and stall precursors.

Keywords: compressor; unsteadiness of tip leakage flow; circumferential propagation; stall inception; power spectrum density; root-mean-square

0 Introduction

Rotating stall represents the primary factor causing compressors to enter unstable operating conditions, and has been the subject of intensive international research for several decades. Early studies focused primarily on the characteristics of stall phenomena itself, such as stall cell patterns and propagation speeds, employing experimental investigations and system modeling approaches [1-2]. To effectively predict and avoid stall onset, substantial research has been conducted on stall precursor detection and triggering mechanisms [3-7], which has become the fundamental basis for currently established active/passive control methods.

Present research on stall precursors manifests in two main aspects: detection methodologies for stall precursors, and pre-stall precursor characteristics—specifically flow features in the blade tip region dominated by tip clearance leakage flow. The former is exemplified by MIT’ s work on long-length-scale stall precursor detection [3-4] and Cambridge University’ s Day [5] on short-length-scale stall precursor detection. Since most actual compressor stall precursors exhibit the latter behavior, this has attracted considerable attention from researchers. Inoue et al. [6] discovered that the tip region exhibits strong unsteady fluctuations near stall conditions, with frequencies related to blade passing frequency, a phenomenon that can be used to identify stall precursor emergence. Hoying et al. [7] through numerical calculations found that during spike stall precursor development, the interface formed by the dynamic balance between mainstream flow and tip clearance leakage flow moves upstream along the blade with compressor throttling. Vo [8] further investigated a low-speed axial compressor and proposed criteria for spike-type stall precursors, which have also proven applicable to transonic axial compressors [9].

Understanding of the flow field ultimately serves practical applications, and researchers internationally have conducted corresponding detection and control studies on tip clearance leakage flow [10-16]. Tahara et al. [10] successfully predicted and controlled compressor stall precursor onset by detecting the degree of periodic disruption in wall pressure sawtooth waves using correlation analysis, speculating that sawtooth wave disruption relates to blade tip leakage flow. Tong Zhiting et al. [13] proposed a micro-jet control strategy based on autocorrelation analysis detection, successfully expanding compressor flow stability margin. The present authors [15-16] also designed a tip air injection control system based on cross-correlation analysis of wall pressure sawtooth wave disruption. Numerous experimental and numerical results demonstrate that the tip region exhibits periodic unsteady fluctuation characteristics near large-clearance, low-flow-rate operating conditions, a phenomenon confirmed across an increasing number of low-speed and transonic axial compressors [17]. Although different researchers employ varying terminology to describe this phenomenon, the described phenomena themselves show no essential differences, all being closely related to tip clearance leakage flow. The international community has widely adopted the term "rotating instability," with studies [18-20] investigating the frequency and axial propagation characteristics of unsteady fluctuations in the tip region. Reference [21] examined the unsteady frequency and flow field characteristics in the rotor tip region dominated by periodic unsteady fluctuations of tip clearance leakage flow, elaborating on the driving mechanism from a pressure differential perspective. These studies indicate preliminary international recognition of tip leakage flow unsteadiness and its important role in compressor stall processes.

However, understanding remains limited regarding the intrinsic connection between tip leakage flow unsteadiness and stall precursors. Young [22] from Cambridge University experimentally measured and analyzed the unsteady fluctuation frequency and circumferential propagation characteristics in the tip region with asymmetric clearance. Geng Shaojuan [23] conducted full-annulus numerical simulations on a low-speed axial compressor, investigating the circumferential propagation characteristics of tip leakage flow unsteadiness and their evolution during throttling.

Based on the aforementioned analysis of stall precursor characteristics, triggering mechanisms, and prediction methods, research has focused on tip region flow dominated by tip clearance leakage flow. Moreover, some connection exists between stall precursor generation/propagation and unsteady fluctuations in tip clearance leakage flow. This paper takes this as its starting point, experimentally investigating the circumferential propagation characteristics of tip leakage flow unsteady fluctuations during compressor throttling, providing a basis for understanding and clarifying the transition from tip leakage flow unsteadiness to stall precursor formation.

1 Experimental Facility and Measurement Methods

The experiments were conducted on a low-speed axial compressor, with relevant aerodynamic parameters described in reference [24]. To obtain detailed unsteady wall pressure measurements along the chordwise and circumferential directions, the sensor installation arrangement shown in [Figure 1: see original paper] was employed. Three rows of dynamic pressure sensors were installed along the chordwise direction, with two additional rows arranged circumferentially near the blade leading edge. To ensure accurate capture of the compressor wall flow field and guarantee repeatability of the compressor characteristic line, multiple repeatability tests were performed, as shown in [Figure 2: see original paper]. Dynamic measurements were conducted only after confirming good repeatability.

2 Circumferential Propagation Characteristics of Tip Leakage Flow Unsteadiness

Based on measurements from the CH1-CH6 sensors arranged chordwise as shown in [Figure 1: see original paper], wall static pressure contours were obtained for different flow conditions. The wall pressure contours measured by three sensor rows under high-flow (Φ=0.58) and near-stall (Φ=0.48) conditions were compared. [Figure 3: see original paper] and [Figure 4: see original paper] present the wall pressure contours measured by the three sensor rows under different flow conditions. Based on the rotation direction indicated in the figures, the propagation speed of individual blades matches the compressor rotational speed (NS). Since blade rotation speed dominates, no other disturbance generation or propagation is visible. However, extensive literature [17,24,25] has established that when tip clearance exceeds a certain critical value, strong tip leakage flow unsteadiness emerges as the compressor approaches stall. Therefore, this study also begins with tip leakage flow unsteadiness to analyze wall static pressure disturbances.

[Figure 5: see original paper] presents PSD analysis of unsteady pressure at different chordwise positions under three operating conditions. The figure clearly shows the amplitude of characteristic frequency bands around 0.4BPF increasing with compressor throttling, with previous work [17] confirming this characteristic band corresponds to tip leakage flow unsteadiness. Under near-stall conditions, tip leakage flow unsteadiness is particularly strong at approximately 20% chord length. Besides the periodic disturbances from tip leakage flow unsteadiness, no other disturbances are visible. Therefore, band-pass filtering was employed to investigate the circumferential propagation characteristics of disturbances in different frequency bands.

As the analysis indicates, tip leakage flow unsteadiness distributes within the 0.26-0.6BPF frequency band. This band was first band-pass filtered and the wall pressure spectrum replotted, as shown in [Figure 6: see original paper], presenting wall static pressure contours at near-stall condition (flow coefficient 0.48). Based on the rotation direction in the figure and the region indicated by black arrows detected by the three chordwise sensor rows in [Figure 1: see original paper], clear circumferential propagation characteristics exist for this frequency band signal, with a propagation speed of approximately 0.43NS. In contrast, when other frequency bands below BPF were band-pass filtered under the same flow condition, as shown in [Figure 7: see original paper] and [Figure 8: see original paper] for 0.08-0.2BPF and 0.7-0.96BPF respectively, no circumferential propagation phenomena were observed, unlike the clear circumferential propagation of tip leakage flow unsteadiness shown in [Figure 6: see original paper].

3 Evolution of Circumferential Propagation Characteristics

The previous analysis of circumferential propagation characteristics detected by three chordwise sensor rows revealed that only disturbances in the frequency band corresponding to tip leakage flow unsteadiness propagate circumferentially at speeds below compressor rotational speed. To more detailedly analyze the variation in circumferential propagation speed during throttling, 15 sensors were arranged circumferentially at the axial location where tip leakage flow unsteadiness is strong (20% axial chord). Additionally, 15 sensors were installed near the blade leading edge to capture the dynamic process from tip leakage flow unsteadiness circumferential propagation to stall precursor circumferential propagation.

[Figure 9: see original paper] illustrates the evolution of circumferential propagation speed for the tip leakage flow frequency band (0.26-0.6BPF) at the 20% axial chord location during compressor throttling. Under high-flow conditions, tip leakage flow unsteadiness is relatively weak (as shown in the PSD of [Figure 5: see original paper]), and circumferential propagation speed remains influenced by blade rotational speed at 1NS. As the compressor throttle valve closes, at flow coefficient 0.54, a propagation speed different from blade rotation emerges at 0.404NS. With continued reduction in flow coefficient, the circumferential propagation speed of tip leakage flow unsteadiness continuously increases, as indicated by the slope of black arrows in the figure. Particularly during stall inception ([FIGURE:9(e)]), the figure simultaneously shows both the tip leakage flow unsteadiness propagation speed (0.48NS) and the stall precursor propagation speed. The stall precursor propagation speed, consistent with that measured by nine circumferentially uniform sensors in [Figure 10: see original paper] at 0.578NS, demonstrates that tip leakage flow unsteadiness propagation speed continuously evolves toward the stall precursor propagation speed, meaning the intensifying circumferential propagation of tip leakage flow unsteadiness ultimately leads to stall precursor generation.

4 Conclusions

Through experimental measurements on a low-speed axial compressor, this study obtained detailed chordwise and circumferential wall unsteady pressures, investigating the spectral characteristics, circumferential propagation features, and evolutionary processes of tip leakage flow unsteadiness, providing a basis for numerical analysis. The following conclusions are drawn:

1) Circumferential propagation of disturbances occurs only after the emergence of tip leakage flow unsteadiness during compressor throttling.

Through band-pass filtering of different frequency band signals, only disturbances characterized by tip leakage flow unsteadiness exhibit circumferential propagation.

2) Following the onset of tip leakage flow unsteadiness during throttling, its circumferential propagation speed increases with further flow reduction. The experimentally measured stall precursor circumferential propagation speed is 0.578NS, while tip leakage flow unsteadiness propagation speed is approximately 0.48NS before stall precursor generation, indicating a direct relationship between stall precursor circumferential propagation and tip leakage flow unsteadiness circumferential propagation.

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