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Quantitative evaluation of the unsteady behaviors of the tip leakage vortex in a subsonic axial compressor rotor

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ABSTRACT

Tip leakage flow is inherently an unsteady flow phenomenon, which plays an important role in compressor stability. A quantitative evaluation of the unsteady behaviors of tip leakage vortex will help reveal the effect of tip leakage flow on the compressor characteristics. In this paper, stereoscopic particle image velocimetry (SPIV) is used to investigate the unsteady behaviors of tip leakage vortex near the rotor tip region in a low-speed axial compressor test facility. By using a vortex identification method, the size, location, the number and some other parameters of the TLV in the instantaneous realizations of the SPIV results are extracted. Based on the statistical analyses of these critical parameters, the unsteady behaviors of the TLV (vortex wandering, vortex splitting, and vortex breakdown) are quantitatively evaluated. A parameter is defined to quantitatively evaluate the intensity of the tip leakage vortex wandering, and it is found that the intensity of vortex wandering increases slowly at first but then increases rapidly as the TLV propagates downstream. Vortex splitting is found to start at different streamwise locations for different mass flow rate conditions, and from the initial position of the vortex splitting the average number of TLV increases with the streamwise location. The backflow induced by the vortex breakdown in the tip leakage flow is significant in the SPIV results. At last, the effect of the TLV's wandering, splitting, and breakdown on the evolution of the blockage is also discussed.

1. Introduction

It is well known that the tip leakage flow (TLF) plays an important role not only on the efficiency and the pressure rise but also on the stability operating range of a compressor [1–3]. In recent years, many researchers have found that the TLF is inherently an unsteady flow phenomenon. This unsteadiness is a natural unsteadiness in turbomachinery that not related to rotor/stator interaction frequencies. In the previous researches, various flow phenomena involving the unsteadiness of the tip leakage vortex (TLV) may include rotating stall, self-induced unsteadiness of TLV [4], rotating instability [5], oscillations of the TLV [6], and vortex shedding. And according to these studies, the features of the unsteadiness of TLV could be classified into vortex wandering, vortex splitting, and vortex breakdown, and all the features are believed to have significant relationships to some important flow phenomena in compressors.

The unsteady wandering of the tip leakage vortex, which features as the swing of tip leakage vortex core trajectory [6–10], was firstly observed in a high-Reynolds number pump by Zierke et al. [6] and Straka and Farrell [7] And lately Tan et al. [11] also found this phenomenon in an optically index matched compressor facility (with water as the flow media). Due to its effect on the accuracy of the time-averaged flow measurements [6,7] and the stability of the turbomachinery [8–10], many studies have been conducted to reveal the mechanism and the influence on the whole flow. By using LES simulations, You et al. [9] detected the vortex wandering in a cascade configuration and found that the tip leakage vortex mainly wandered along the pitchwise direction. Using dynamic casing pressure measurements and unsteady RANS simulations, Marz et al. [8] found that vortex wandering could occur even at intermediate loading conditions of a low speed axial flow compressor, and it may be a precursor of rotating instability. In the same compressor, after detailed zonal LES analysis, Boudet et al. [10] proposed a mechanism from vortex wandering to rotating instability, and pointed out that the vortex wandering appears to be a major contribution to noise radiation.

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Nomenclature

C_p	static pressure rise coefficient, $(P_{out} - P_{in})/(0.5\rho V_{mid}^2)$	γ	the ratio of the vortex diameter in the ensemble-averaged flowfield to the mean vortex diameter in instantaneous flowfields
φ	mass flow coefficient, V_{aix}/V_{mid}	ρ	air density (kg/m^3)
V_{aix}	axial flow velocity (m/s)	X, Y, Z	coordinates of SPIV measuring planes
V_{mid}	blade mid-span speed (m/s)	U, V, W	velocity in X, Y, Z directions, respectively (m/s)
A_b	local reduced throughflow area caused by the TLV (m^2)	DE	compressor design condition
B	blockage coefficient	NC	compressor near-choke condition
B_m	mass-flow-based blockage coefficient	NS	compressor near-stall condition
m_b	local reduced mass flow rate caused by the TLV	SS	blade suction surface
m_t	total mass flow rate of the compressor	PS	blade pressure surface
θ	circumferential direction	PIV	particle image velocimetry
r	spanwise direction	SPIV	stereoscopic particle image velocimetry
Re_{chord}	Reynolds number calculated based on rotor tip chord length	TLF	tip leakage flow
ω_z	out-of-plane vorticity	TLV	tip leakage vortex
Ω	rotor rotational speed	SGP	tip leakage vortex stable growth phase
P	static pressure (Pa)	USP	tip leakage vortex unsteady phase
L	distance downstream of the blade leading edge (m)	TMP	tip leakage vortex turbulence mixing phase
C	length of the rotor tip chord (m)	in	compressor inlet
PW	passage width in the SPIV measurement planer (m)	out	compressor outlet
D	diameter of the TLV (m)	ext	outer edge of the core of the TLV
σ	vortex wandering intensity		

The unsteady splitting of the tip leakage vortex was first proposed by Liu et al. [12,13]. By applying the SPIV in a low-speed axial compressor, they found that the tip leakage vortex would split into some small vortices. These small vortices interacting with the surrounding flow enlarges the region with high turbulence intensity and results in a distinct expansion of the low momentum flow region in the vortex core. Similar to the vortex wandering, vortex splitting was found at both near-stall condition (high loading) and design condition (intermediate loading).

Vortex breakdown was first used to describe the abrupt change in the structure of the core of a swirling flow [14]. It was initially observed in the external flow, in the leading edge vortices formed on delta wings at large angle of attack. Until the end of last century, Furukawa et al. [15] and Schlechtriem and Lötzerich [16] at almost the same time observed this phenomenon in tip leakage flow in compressors: no rolling-up of the leakage vortex downstream of the rotor, the disappearance of the casing wall pressure trough, the large spread of the low-energy fluid accumulating on the blade pressure side, and the high pressure fluctuation on the pressure side. Since then many studies were conducted to clarify the fluid mechanism of vortex breakdown and the influence of vortex breakdown on the performance of the compressor [3,15–22]. By far, the universal accepted distinctive features of the vortex breakdown are the existence of a stagnation point on the centerline of vortex structure and the induced backflow in the tip leakage flow. Vortex breakdown is substantially different from vortex wandering and splitting, and it is the strongest unsteady behavior of tip leakage vortex. In general, vortex breakdown, which happens at near-stall conditions or high loaded conditions, could induce much flow blockage in the rotor tip region and was proved to have a major impact on stall [3,16–22].

Although the gross feature of the above unsteady behaviors of the tip leakage vortex has been known for some time, a quantitative description on the unsteady characteristic of TLV is still scarce. Besides, it is well known that the unsteady behaviors of the TLV (vortex wandering, vortex splitting, and vortex breakdown) have effect on the end-wall blockage, but it is still obscure which behavior is the predominant factor. As the particle image velocimetry (PIV) technique can capture the instantaneous snapshots of flow structures, it has been employed to investigate the tip leakage flow/vortex by many researchers [23–26]. In the present paper, stereoscopic particle image velocimetry (SPIV) is used to investigate the unsteady behaviors of tip leakage vortex near the rotor tip region in a low-speed axial compressor test facility. By using a vortex identification method, the size, location, the number and some other parameters of the TLV in the instantaneous realizations of the SPIV results are extracted. Based on the statistical analyses of these critical parameters, the unsteady behaviors of the TLV (vortex wandering, vortex splitting, and vortex breakdown) were quantitatively evaluated. Meanwhile, the effect of the TLV's wandering, splitting, and breakdown on the evolution of the blockage is also discussed. All of these discussions will be helpful for tip leakage flow modeling, CFD validation and also the development of flow control methods in compressors.

2. Experimental setup and layout

2.1. Tested compressor

The experiment is conducted in the low-speed large-scale axial compressor facility of Beihang University, which is composed of a single-stage axial compressor and inlet guide vanes (IGVs), as shown in Fig. 1. A large contraction ratio bellmouth with a 1.8 m outer diameter lemniscate profile equipped with flow straightener is used to provide uniform and steady inlet flow, and a throttle is used to alter the operating condition of the compressor. The casing out diameter of the compressor is 1 m, and the hub diameter is 0.6 m. As this low-speed large-scale axial compressor facility is used to model the rear stage of the high pressure compressors, in which the typical rotor tip clearance is 1.5–3.0% blade chord length, the rotor tip clearance in the present compressor is 2.3% blade chord length. More detailed design parameters of the compressor are summarized in Table 1, which were also introduced by Du et al. [27] Here, it should be noted that the present investigation was conducted on the same compressor facility with the previous studies [12,13], but with different IGV, rotor, and stator. Other than the rotor tip gap, the most prominent difference between these two compressor configurations is the blade loading i.e., at the design condition, the present rotor blade loading coefficient is about 0.52, while the previous is 0.35.