UNSTEADY KINEMATICS OF MULTISTAGE AXIAL COMPRESSOR SHROUDED CAVITY FLOW

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ABSTRACT

An experimental investigation has been performed in a low-speed shrouded multistage axial compressor to investigate the impact of mainstream flow on unsteady shrouded cavity flow. A single 45° slanted hot-wire has been used to obtain the ensemble-averaged three-dimensional velocity vectors inside the upstream and downstream cavities of 3rd stage stator, which are identical to known shrouded stator cavity flow structures. The mechanism of the unsteadiness inside shrouded stator cavities is analysed; intermittent radial movements created by the superposition of 2nd stage stator and 3rd stage rotor wakes suppress local ingress due to the pressure side of 3rd stage rotor, creating pairs of local ingress-egress inside the upper cavity of 3rd stage shrouded stator. In addition, the variation of hubside velocity downstream of 3rd stage stator alters the position of recirculation inside downstream 3rd stage stator cavity.

INTRODUCTION

Compared with cantilevered stator configuration, the flow in stators shrouded at the hub shows the hubside corner separation at the stator suction side (SS), increasing the hubside loss and blockage (Swoboda et al., 1998; Campobasso et al., 1999; Lange et al., 2010). About ~20% of hubside blockage created by hubside corner separation was reported, compared with about ~5% at stator midspan (Joslyn and Dring, 1985).

In addition, the labyrinth seal leakage flow of shrouded stator emerges from the upper cavity of shrouded stator, further reducing the hubside momentum; and the increased mass flow rate or reduced tangential velocity of labyrinth seal leakage flow further degrades compressor performances (Wellborn and Okiishi, 1999; Wellborn, 1999; Demargne and Longley, 2000; Kim et al., 2012; Marty and Aupoix, 2012; Schrapp et al., 2019). The low-momentum labyrinth seal leakage flow heads towards the stator pressure side (PS), then to the stator passage suction side (SS) due to the PS-SS pressure gradient inside the stator passage (Wellborn and Okiishi, 1996; Kim et al., 2012). This labyrinth seal leakage flow widens the width of the hubside low-momentum region and creates additional vortical structure nearby hubside corner separation. (Wellborn, 2001; Demargne and Longley, 2000; Fröebel et al., 2010; Kim et al., 2012).

The reduced momentum of labyrinth seal leakage flow are created by the vortical structures inside the cavities between the labyrinth seals and shroud (Heidegger et al., 1996; Wellborn, 2001; Kim et al., 2012; Childs, 2004; Denecke et al., 2005; Flores and Seume, 2014; Chupp et al., 2006; Pfau, 2013). The magnitude of vortical structures and loss vary

Figure 1. Schematic of SNU Compressor

depending on geometry (Heidegger et al., 1996). In addition, pitchwise variation of radial velocity inside cavities are observed due to potential effect of downstream stator leading edge and upstream blade wakes (Wellborn, 2001; Kim et al., 2012). Furthermore, the kinematics of flow in axial compressor is inherently unsteady by the relative motions between rotor and stator. The transportation of rotor wake into the downstream stator passage creates unsteady stator passage flow (Smith, 1966; Kerrebrock and Mikolajczak, 1970; Valkov and Tan, 1999; Mailach et al., 2008). Previous study (Wellborn, 2001) has found unsteadiness in velocity and local transient ingress/egress of upstream/downstream cavity flow of shrouded stators. Thus, it is expected that the unsteady variation of shrouded cavity flow affects the performances of shrouded axial compressor, which remains unanswered.

Therefore, the interaction between the cavity flow and mainstream flow of shrouded axial compressor should be investigated to reflect its impact on compressor performances. As a first step, the impact of mainstream flow on unsteady shrouded cavity flow will be discussed experimentally in this study, focusing on the unsteady kinematics of shrouded cavity flow.

METHODOLOGY

The present study has been conducted in a low-speed four repeating-stage shrouded axial compressor installed at Turbomachinery Laboratory, Seoul National University (Figure 1). It is an open-type axial compressor operated by a 55 kW DC motor. The ingested flow passes through a circular filter screen, an upstream bellmouth, and an ogive to reach the four-stage compressor section and exits the compressor via a downstream throttle. The blades have been designed by Doosan Heavy Industries & Construction, and the compressor is powered by a 55-kW DC motor and a gearbox. Parameters of the SNU Compressor are summarized in Table. 1, and the details of the SNU compressor can be found in Lee (2019).

Measurements have been conducted at $\phi=0.355$, $\psi=1.292$. Three-dimensional unsteady velocities have been measured at six planes (Planes 3.5a, 3.5b, 3.5c and Planes 4.0a, 4.0b, 4.0c), ranging from -20% to -2% span (Planes 3.5a, 3.5c, 4.0a, 4.0c) and -20% to 50% span (Planes 3.5b and 4.0b) to measure the three-dimensional velocity distribution inside shrouded cavities and mainstream flow upstream and downstream of 3rd stage stator. The stator shroud has three-knife labyrinth seals (Figure 2).

Figure 2 Measuring Planes and Locations

Radial and circumferential measurements have been performed using a single-element 45° slanted hot-wires (Dantec Dynamics, 55P12), with a prong diameter 2.5%, and wire length 1.67% of the passage span. Three measurements have been performed at a single measurement point at three different sensor yaw angle intervals of 40° . These raw-voltage signals have been acquired at known azimuthal rotor orientations using simultaneously collected encoder (Baumer, HOG14) signals. These signals have been collected by a DAQ board (National Instruments, PXI-4492) at a sampling rate of 200 kHz (note that the blade passing frequency of the compressor is 866.67 Hz), and low-pass filtered with cut-off frequency 100 kHz to avoid alias. Approximately 80 signals have been obtained per single timestep, single yaw angle, at a given measuring point. The signals have been phase-locked ensemble-averaged and converted into velocity vectors using the technique of Shin et al. (1994). The root-mean square of collected raw-voltage is on average 1.21% of ensemble-averaged raw voltage signals. Uncertainties (with 95% confidence interval) of 6.67% accuracy for the U and 1.5° for flow angle are obtained (Coleman and Steele, 2009).

Parameters	Numbers
$Re(CU_t/v)$	195,500
Design RPM	1,000
$\dot{m}_d$	5 kg/s
ϕ_d	0.355
ψ_d	1.292
Tip clearance (% S)	1.40 %
Labyrinth Seal Clearance (% S)	0.93 %
Diameter	1,000 mm
Hub to tip ratio	0.85
Total to Total Pressure Ratio	1.024
# of blades	53 (IGV) 52 (Rotor) 88 (Stator)
C (midspan)	56 mm (Rotor) 50 mm (Stator)
S	75 mm

Table 1. Parameters of SNU Compressor

RESULTS AND DISCUSSION

Kinematics of Upstream Cavity Flow of Shrouded Stator

Figure 3 illustrates the instantaneous colour contour distribution of axial, radial and tangential velocities and secondary velocity vectors in the upper cavity at 50% pitch, $T/T_0 = 60\%$ in Plane 3.5b. At -20% span, axial velocity is negative, but increases as the upper cavity flow moves closer to the mainstream passage flow. In addition, positive radial velocity is dominant at planes 3.5a and 3.5b (close to rotor) and negative radial velocity is observed at Plane 3.5c (close to stator). This is due to the labyrinth seal leakage flow entering the upstream cavity. At first, the labyrinth seal leakage flow axially enters the upper cavity, and is turned radially. Because of this behaviour, the secondary velocity vector at the lower cavity shows clockwise distribution, with the negative axial velocity at the lower span of cavity. Nearby the mainstream passage, a vortical structure created by the cavity flow entering the mainstream passage is observed (Demargne and Longley, 2000; Wellborn, 2001). Due to this vortical structure, negative radial velocity is observed in Plane 3.5c. Finally, tangential velocity distribution inside cavity up to $\sim 10\%$ span remains constant at about $\sim 0.36 U_{tip}$. Near the mainstream passage region, tangential velocity increases due to the mainstream passage flow. Overall, the measured velocity contours and secondary velocity vector distributions in the upper shrouded stator cavity are consistent with those of the previous investigations.

The 3rd stage rotor wake leads to unsteady variation of the cavity flow structure. Figure 4 shows axial, radial velocity and secondary velocity distributions of plane 3.5b, including both the mainstream passage and the upper cavity. A typical low U_x region created by 3rd stage rotor wake is visible as the low axial velocity region. In this region, increased radial velocity is also observed, due to the secondary movement of mainstream flow being pushed by the leaned 3rd stage rotor wake (Lee, 2019). Inside the cavity region (Span < 0%), overall egress (positive radial velocity) is observed throughout the entire cavity, except for the two local ingress (negative radial velocity) regions near 0% span. However, these local ingresses are not caused by the stagnation pressure of downstream stator leading edge (Wellborn, 2001). These local ingresses are first created at the PS of the 3rd stage rotor wake, and they move towards the 3rd stage rotor wake SS before being dispersed. In addition, without the existence of 3rd stage rotor wake, these local ingresses disappear; no ingress is observed nearby the leading edge (LE) of downstream 3rd stage stator (Figure 5), suggesting that the local ingresses are created by the pressure side (PS) of the 3rd stage rotor wake. The possible reason for this phenomenon is wider axial distance between the cavity and downstream stator LE. Comparing the layout of shroud between the LSAC (Wellborn and Okiishi, 1999; Wellborn, 2001) and the SNU Compressor, the axial distance of SNU Compressor is higher. Thus, the suppression of the leakage flow would be confined to nearby the downstream stator LE. In this research, the distance between each measuring plane is $1/6^{\text{th}}$ of the cavity axial clearances due to the shallow gap between the 3rd rotor disk and the shroud of

Figure 3. Axial-Radial Distributions of Ensemble-Averaged Velocity Components inside the Upper Cavity of 3rd Stage Stator at 50% pitch, $T/T_0 = 60\%$

Figure 4. Ensemble-Averaged U_x , U_r and Secondary Velocity Vector Distribution at Plane 3.5b, $T/T_0 = 0\%$

3rd stator. Therefore, it is possible that the local ingress due to the suppression of downstream 3rd stage stator is outside the plane 3.5c.

The location of the local ingresses of upstream cavity show intermittent behaviour; U_x and U_r at different timestep ($T/T_0 = 25\%$) in Figure 6 showed the local egresses nearby the 3rd stage rotor wake PS, unlike the previous timestep ($T/T_0 = 0\%$). In addition, high intermittent radial velocity ($\sim 0.18 U_{tip}$) is observed at the hubside of 3rd stage rotor PS, with its maximum at $\sim 10\%$ span. This phenomenon is due to the multistage effect of the superposition of 3rd stage rotor, and 2nd stator wakes (Lee, 2019). Due to the wider hubside thickness of the 2nd shrouded stator wake hubside corner separation, the mainstream flow nearby the 3rd stage rotor wake experiences higher hubside blockage when 2nd stator and 3rd stage rotor wake are superimposed. Thus, the hubside passage flow near the 3rd stage rotor wake PS has shifted towards the mid-span region, creating the hubside intermittent high positive radial velocity at hubside, creating the local egress nearby 3rd stage rotor wake PS instead of local ingress nearby 3rd stage rotor wake PS as shown in Figure 4. This intermittent local ingress is shifted behind the 3rd stage rotor wake due to the U_θ difference between the 3rd stage rotor wake ($\sim 0.7 U_{tip}$) and cavity flow ($\sim 0.4 U_{tip}$) and is dispersed inside the upper cavity.

These dispersions will increase the pressure inside the shrouded cavity flow, which will further reduce the hubside momentum of shrouded stator during the egress. Not only that, this egress of cavity flow will interact with the upstream 3rd stage rotor wake. Thus, it is expected that the unsteady performance of shrouded stator is worse than that of steady cases, such as the unsteady simulation of Fröbel et al. (2010). Therefore, future study is required to discuss the interaction between the cavity flow and the mainstream flow of shrouded axial compressor.

Kinematics of Downstream Cavity Flow of Shrouded Stator

Figure 7 shows U_x at plane 4.0b, and U_r and secondary velocity distributions in the downstream cavity of shrouded stator at four different pitchwise positions (0%, 25%, 50%, 75% of a stator pitch). A wider low-axial momentum region created by the hubside corner separation is observed, which is typical. The axial-radial distributions of downstream cavity flow show the vortical structure throughout the entire pitch, consistent with Wellborn (2001). Due to the higher axial momentum of hubside passage flow entering the downstream cavity, the passage flow first impacts the downstream rotor disk, is turned radially and enters the downstream cavity. Typical vortical structure by the passage flow entering

Figure 5. Ensemble-Averaged U_x , U_r and Secondary Velocity Vector Distribution at Plane 3.5b, $T/T_0 = 65\%$

Figure 6. Ensemble-Averaged U_x , U_r and Secondary Velocity Vector Distribution at Plane 3.5b, $T/T_0 = 25\%$

Figure 7. Ensemble-Averaged U_x at Plane 4.0, and Pitchwise Distribution of U_r and Secondary Velocity Distribution inside Downstream Cavity of 3rd Stage Stator, $T/T_0 = 0\%$

the downstream cavity is created (Wellborn, 2001).

Thus, ingress of passage flow is dominant in Plane 4.0c, and positive radial velocity is observed in Planes 4.0a and 4.0b (close to stator). However, its radial location varies pitchwise; near the hubside corner separation (0% and 25% Pitch), the vortical structure is at -10% span, whereas at the outside the hubside corner separation (50% and 75% Pitch), the location shifted to $\sim -4\%$ Span.

Figure 8 shows the timewise variation of downstream cavity radial velocity and secondary velocity distributions at 85% span (outside the hubside corner separation). Qualitatively, the downstream cavity flow at all timesteps; the ingress of mainstream flow near the 4th rotor disk, the existence of cavity vortical structure and resulting positive radial velocity in

Figure 8. Ensemble-Averaged Timewise Variation of U_r and Secondary Velocity of Downstream Cavity of 3rd Stage Stator, 85% Span

Plane 4.0a. The center of downstream cavity vortical structure is located at -8% span.

However, the flow varies quantitatively with time - positive radial velocities at $T/T_0 = 25\%$ and 50% are reduced, when 3rd stage rotor wake is passing through the 3rd stage stator passage (Lee, 2019). Thus, similar to the pitchwise variation of downstream cavity flow structures in Figure 6, the downstream vortical structure is affected by the reduced axial velocity.

CONCLUSIONS

The unsteady kinematics of flow shrouded cavities of a multistage shrouded axial compressor has been investigated experimentally, using single 45° slanted hot-wire sensors. The measurements have identified the vortical structures within the upstream and downstream cavities due to the egress of labyrinth seal leakage flow, and the ingress of passage flow into the downstream cavity. In addition, the shrouded cavity flows are affected by the timewise variation of the mainstream flow, which is primarily induced by the 3rd stage rotor wake entering the 3rd stage stator passage. Specifically,

1. Intermittent local ingresses are observed inside the upstream cavity of shrouded stator. These ingresses first originate near at the PS of 3rd stage rotor wake.
2. By the hubside radial movement due to the superposition between 3rd stage rotor and 2nd stator wakes, the local ingress is temporary suppressed, reverted into local ingress.
3. Pitchwise variation of downstream cavity flow structure is observed, which is created by the difference of hubside axial momentum due to the hubside corner separation of shrouded stator passage. Thus, the radial location of vortical structure varies with pitchwise location.
4. The variation of radial location of vortical structure inside the downstream cavity is observed, due to the transportation of 3rd stage rotor wake inside the 3rd stage stator passage.

NOMENCLATURE

Variables

C	Chord [mm]
$\dot{m}$	mass flow rate [kg/s]
P	Pitch
P_s	Static pressure [Pa]
P_t	Total pressure [Pa]
r	Radial direction [mm]
S	Span [mm]
T	Time [s]
T_0	Time for 1 rotor passage rotation [s]
U	Velocity [m/s]
x	Axial direction
ϕ	Flow coefficient
ψ	Pressure coefficient
θ	Tangential direction
$\dot{\theta}$	Rotation speed [Rad/s]
ρ	Density [kg/m ³]
ν	Kinematic viscosity of air [m ² /s]

Subscripts and Abbreviations

d	Design
$_{tip}$	Rotor tip velocity component
LE	Blade leading edge
TE	Blade trailing edge
PS	Blade pressure side
SS	Blade suction side

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