AXIAL SLOT CASING TREATMENT TO IMPROVE THE STALL MARGIN UNDER CIRCUMFERENTIAL TOTAL PRESSURE DISTORTION ON AN AXIAL FLOW COMPRESSOR

ABSTRACT

As a typical stability enhancement method, the axial slot casing treatment (ASCT) has been verified to extend the stall margin under uniform inflow condition. In order to further investigate its stability-enhancing capability under distorted inlet conditions, a series of experimental studies were carried out on a low-speed axial flow compressor. An ASCT structure which can improve the stall margin by 38.75% under uniform inflow was studied. Three types of circumferential total pressure distortion intensities, namely, 0.90%, 4.12%, and 24.75%, are selected to conduct the steady and unsteady measurements with and without ASCT. The results showed that the three distorted inflow have deteriorated the compressor stall margin by 7.87%, 9.19% and 39.08%, respectively. The ASCT can widen the compressor stall margin by 43.86%, 40.27%, and 22.83% under the three distorted inflow conditions, respectively. It demonstrates the strong anti-distortion capability of ASCT. The unsteady pressure signal measured on the casing wall showed that the ASCT could significantly reduce the circumferential propagation speed of stall precursors under all inflow conditions. Under the circumferential total distorted inflows, the stall precursor first appears at the position where the rotor is about to rotate out of the distortion region, and then decays in the undistorted region. The power spectral density of the stall process showed that the ASCT can suppress the disturbance, whose frequency is near the rotating stall frequency band, thereby delaying the occurrence of rotating stall.

Keywords: Compressor, Inlet distortion, Casing treatment, Stall precursor

INTRODUCTION

The operating safety of axial flow compressors in modern aero-engines is usually restricted by the aerodynamic instability. As a kind of aerodynamic instability, rotating stall is considered to be the most unfortunate event in aeroengines and should be avoided at all costs (Day 2016). Previous studies have shown that inlet total pressure distortion can seriously deteriorate the stall margin of the compressor to induce the stall earlier (Longley et al. 1996) (Cousins 2004). Fidalgo et al. (Fidalgo et al. 2012) indicated that the inlet total pressure distortion can greatly affect the capacity of rotor to do work on inflow air, and then causes the reduction of stall margin. As a form of inlet total pressure distortion, circumferential total pressure distortion have drawn more attentions due to the application of multi-spool jet engine and the appearance of

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integral aircraft-engine aerodynamic design. In fact, take-off operation with high angle of attack, cross-winds and nacelle flow separation can bring about inlet circumferential total distortion naturally(Dong et al. 2018). Zhou et al.(Zhou et al. 2019) conducted a full annulus unsteady simulation under the circumferential total pressure distortion, the results indicated that the stall precursor first occur in those blade tips with high blade loads. Zhang and Vahdati(Zhang and Vahdati 2019) demonstrated that the tip leakage vortex exhibits periodic characteristics when the rotor enters and leaves the distortion zone, and found when the clean flow zone fails to eliminate the flow separation generated in the distortion zone, the compressor will stall. Therefore, to ensure the safe operation of aero-engines, wide stall margin of the compressor shall be guaranteed even under distorted inflow conditions, which is currently demanding prompt solution.

At present, the effective stability enhancement measures mainly include tip injection (Li et al. 2019), adjustable angle guide vanes(Shaw et al. 2014), blade modification design(Madden and West 2008), and casing treatment (CT) (Prince et al. 2015), etc. Among them, the casing treatment, namely axial slot and circumferential groove CTs, has received widespread attention because of its low-cost, easy-processing, and stability-enhancing ability(Brandstetter et al. 2015)(Pixberg et al. 2013). Prince et al.(Prince et al. 2015) pointed out when the compressor is tip-critical stall, the casing treatment can effectively extended the stable working range of the compressor under uniform inlet condition. Takata et al. (Takata and Tsukuda 1977) and Bilwakesh et al. (Bilwakesh et al. 1971) conducted experiments on various types of CTs, and indicated that the axial slot casing treatment (ASCT) has the highest stability-enhancing capability. The experimental results obtained by Li et al.(Li et al. 2019) also confirmed this conclusion. Du et al.(Du et al. 2019) designed a kind of ASCT on a mixed-flow compressor, and obtained 20% stall margin improvement by suppressing the spillage of interface between tip leakage flow and mainstream flow.

The above researches on CTs are all carried out under uniform inflow, and there are few relevant studies under the inlet circumferential total pressure distortion. Bilwakesh et al.(Bilwakesh et al. 1971) indicated that the ASCT has little difference in stall margin improvement with and without circumferential total pressure distorted inflow. The research team in Beihang University proposed a stall precursor suppression (SPS) CT and tested under inlet circumferential total pressure distortion (Dong et al. 2018)(Li et al. 2013). Under the uniform inflow, the SPS casing treatment can improve the stall margin for 3%-5% without significantly changing the pressure rise characteristics. Under circumferential total pressure distorted inflow, the SPS casing treatment can also widen the stall margin for 6%-8%.

The abovementioned results show that the stability-enhancing capability of ASCT was only verified under a single distortion intensity. When the compressors suffer from different intensities of inlet circumferential total pressure distortion, the stability-enhancing capability of the ASCT is still in question. Therefore, the most traditional ASCT is selected to conduct the experimental measurements under different circumferential distortion intensities, and the stability enhancement mechanism and its effect on stall precursors under different inlet distorted intensity are evaluated in the current study. The paper is divided into the following parts. Previous studies are briefly introduced in Section 1. The test rig and measurement setup are described detailly in Section 2. In Section 3, the influence of the ASCT on compressor performances and stall routes are studied under distorted inflows, and its stability enhancement mechanism is discussed. The conclusions are summarized in Section 4.

TEST RIG AND MEASUREMENT SETUP

Test Rig

The experimental study was conducted on a low-speed single-rotor axial flow compressor with a designed speed of 2400 rpm, as shown in Fig.1. Table 1 shows the main parameters of the compressor. The rotor blade was designed to model a high-pressure stage. The number of rotor blades is 60, and the tip clearance is 0.8mm. The opening degree of the outlet throttle valve is adjusted at a constant speed by a stepping motor. The experimental measurement diagram is shown in Fig.2. The flow rate is converted by the data of four steady static pressure measurement points at plane A, which is 22.2 axial chords ($C_{ax}$) upstream from the blade LE. The circumferential distortion generator is installed at plane B, 410mm upstream of the blade LE. In order to measure the total pressure profile downstream of the distortion generator, five dynamic five-hole comb probes are symmetrically distributed on plane C at a distance of 1.9 $C_{ax}$ upstream from the blade LE. Eight high-frequency pressure sensors located 0.15 $C_{ax}$ upstream of the blade LE, are symmetrically mounted around the annulus at plane D. The outlet steady static pressure measuring hole is set at plane E, 18.5 $C_{ax}$ downstream of the blade LE. The sampling rate of the unsteady measurement is 100kHz. Compared with the blade passing frequency (BPF) of approximately 2.4 kHz, this sampling rate is sufficient for dynamic measurements.
Figure 1 The photo of test rig

![Figure 1]

Figure 2 Diagram of experimental measurements

![Figure 2]

Table 1 Key Parameters of Test Compressor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design speed (rpm)</td>
<td>2400</td>
</tr>
<tr>
<td>Number of rotor blades</td>
<td>60</td>
</tr>
<tr>
<td>Design mass flow rate (kg/s)</td>
<td>2.9</td>
</tr>
<tr>
<td>Rotor tip chord (mm)</td>
<td>36.3</td>
</tr>
<tr>
<td>Rotor tip stagger angle (deg)</td>
<td>39.2</td>
</tr>
<tr>
<td>Hub-tip ratio</td>
<td>0.75</td>
</tr>
<tr>
<td>Tip clearance (mm)</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Geometry Parameters of ASCT

The ASCT studied in this paper is composed of 240 equal axial slots, as shown in Fig.3(Du et al. 2015). The ratio of the number of slots to the number of blades is 4:1. Each axial slot extends from the leading edge to the trailing edge. The slot is parallel to the rotation axis of the rotor and were inclined by 60° along the direction of the rotor rotation against a
meridian plane, with a depth-to-width is 1.67. The ratio of the depth of the slot to the blade height is 0.12. The open area ratio is 66.7%.

![Figure 3 Axial Slot Casing Treatment(Du et al. 2015)](image)

**Circumferential Distortion Generator**

The circumferential distortion generator is shown in Fig. 4. It can generate different circumferential total pressure distortion intensities by adjusting the height of the plate at the position of plane B in Fig. 2. The relative plate depth $H$ is defined as shown in Equation (1). In the current study, the relative plate depth $H$ is selected as 0.25/0.5/0.75 to generate three different circumferential distortion intensities.

$$H = \frac{S}{L} \quad (1)$$

![Figure 4 Board Depth of Circumferential Distortion Generator](image)

The dynamic comb probes downstream of the distortion generator are used to measure the total pressure profile at the 0.45 flow coefficient, as shown in Fig. 5. It can be seen that the three configurations of the plate depths have produced circumferential distortions with different intensities. As the plate depth increases from 0.25 to 0.75, the total pressure in the distortion region decreases gradually. In this study, the DC(60) is used to quantify the distortion intensities. It is defined as Equation (2).
Figure 5 Total Pressure Distortion Profile

\[
DC(60) = \frac{P_{t,ave} - P_{t,dis,ave}}{0.5 \rho U_{mid}^2}
\]  

(2)

where \( P_{t,ave} \) is the average total pressure of the entire profile, \( P_{t,dis,ave} \) is the average total pressure in the 60-degree sector in the center of the distortion region, \( \rho \) is airflow density, \( U_{mid} \) is the tangential velocity at the mid-span that is defined by Equation (3),

\[
U_{mid} = \frac{\pi N r_m}{30}
\]  

(3)

where, \( N \) is rotor speed, \( D_m \) is radius of middle span. The distortion intensities represented by \( DC(60) \) are shown in Table 2. When the relative plate depth (H) is changed from 0.5 to 0.75, the distortion intensity is greatly enhanced.

<table>
<thead>
<tr>
<th>Case</th>
<th>DC(60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>0</td>
</tr>
<tr>
<td>Distortion: H=0.25</td>
<td>0.90%</td>
</tr>
<tr>
<td>Distortion: H=0.5</td>
<td>4.12%</td>
</tr>
<tr>
<td>Distortion: H=0.75</td>
<td>24.75%</td>
</tr>
</tbody>
</table>

Table 2 DC(60) of Test Cases

Experimental Measurement Parameters

In this study, the static pressure rise coefficient is used to reflect the pressure rise characteristics of the compressor. It is defined as Equation (4),

\[
\Psi = \frac{P_{s, outlet} - P_{t, inlet}}{0.5 \rho U_{mid}^2}
\]  

(4)

where, \( P_{s, outlet} \) is the outlet static pressure , \( P_{t, inlet} \) is the inlet total pressure. The flow coefficient is defined in Equation (5),

\[
\Phi = \frac{V_{x, inlet}}{U_{mid}}
\]  

(5)

where, \( V_{x, inlet} \) is the inlet axial speed. The \( V_{x, inlet} \) is defined in Equation (6),

\[
V_{x, inlet} = \sqrt{2(P_{t, inlet} - P_{s, inlet}) / \rho}
\]  

(6)

where, \( P_{s, inlet} \) is static pressure at inlet. The definition of stall margin is shown in Equation (7),

\[
SM = \left(\frac{\Psi_s / \Phi_s}{\Psi_d / \Phi_d} - 1\right) \times 100\%
\]  

(7)

where, \( \Psi_s \) and \( \Phi_s \) are the pressure rise coefficient and flow coefficient of the near stall point under each condition, \( \Psi_d \) and \( \Phi_d \) are the pressure rise coefficient and flow coefficient of the design point under uniform, smooth casing condition. The Equation (8) describes the stall margin variety due to the different inlet conditions in the smooth wall condition.

\[
SMV_{case-SC} = SM_{case-SC} - SM_{uniform-SC}
\]  

(8)

Where, \( SM_{case-SC} \) is one inlet condition with the smooth casing according to Equation (7), \( SM_{uniform-SC} \) is calculated according to Equation (7) for uniform incoming flow with smooth wall. Equation (9) describes the improvement of stall margin obtained by ASCT under the same inlet condition.

\[
SMI = \left(\frac{\Phi_s^{SC}}{\Phi_s^{CT}} - 1\right) \times 100\%
\]  

(9)
Where, $\Phi_{3-SC}$ is the flow coefficient of the near stall point with smooth casing, $\Phi_{3-CT}$ is the flow coefficient of the near stall point with ASCT.

**RESULTS AND DISCUSSION**

**Performance Curves under Inlet Distortions**

Under the above-mentioned inlet conditions, the following comparison of characteristic lines was conducted. Fig 6 showed the pressure rise characteristics of the compressor under various experimental conditions. The abscissa is the flow coefficient $\Phi$, and the ordinate represents the pressure rise coefficient $\Psi$. "SC" represents the smooth casing, "ASCT" represents that axial slot casing treatment was applied. "Uniform" represents the uniform inflow. "DC(60)=0.90%", " DC(60)=4.12%", " DC(60)=24.75%" represents the distorted inflow under 0.90%, 4.12%, 24.75% distortion intensities, respectively. Table 3 showed the SMV/SMI of each experimental condition.

![Figure 6 Pressure Rise Characteristic Curves](image)

**Table 3 SMV/SMI of Test Cases**

<table>
<thead>
<tr>
<th>Case</th>
<th>$SMV_{case-SC}$</th>
<th>$SMI_{CT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform-SC</td>
<td>0</td>
<td>/</td>
</tr>
<tr>
<td>DC(60)=0.90%-SC</td>
<td>-7.87%</td>
<td>/</td>
</tr>
<tr>
<td>DC(60)=4.12%-SC</td>
<td>-9.19%</td>
<td>/</td>
</tr>
<tr>
<td>DC(60)=24.75%-SC</td>
<td>-39.08%</td>
<td>/</td>
</tr>
<tr>
<td>Uniform-ASCT</td>
<td>/</td>
<td>38.75%</td>
</tr>
<tr>
<td>DC(60)=0.90%-ASCT</td>
<td>/</td>
<td>43.86%</td>
</tr>
<tr>
<td>DC(60)=4.12%-ASCT</td>
<td>/</td>
<td>40.27%</td>
</tr>
<tr>
<td>DC(60)=24.75%-ASCT</td>
<td>/</td>
<td>22.83%</td>
</tr>
</tbody>
</table>

Compared with the uniform inflow condition, all the distortion conditions will move the characteristic line to the left. This is because the circumferential distortion generator causes the axial velocity of the distortion zone to decrease, and the average axial velocity of the total cross-section decreases, which in turn leads to a decrease in the flow coefficient. The stall margin gradually deteriorates as the distortion intensity increases. Among them, the distorted intensity of 24.75% makes the stall margin drop the most serious, reaching -39.08%. As shown in Fig 7, ASCT has obvious effect of extending the stall margin for all three distortion conditions. Under the condition of uniform incoming flow, ASCT increases the stall margin by +38.75%. Under the three circumferential distortion intensities of 0.90%, 4.12%, and 24.75%, ASCT also produced significant effects, and the stall margin improvement was +43.86%, +40.27%, and +22.83%, respectively. Observed from the Fig 8, as the distortion intensity increases, SMV does not change linearly, but has a peak. That is, in the condition near a certain distortion intensity (about 0.90%-4.12%), ASCT brings more relative stall margin improvement.

![Figure 7 SMV of Test Cases](image)

![Figure 8 SMI of Test Cases](image)
Time-frequency Analysis of Stall Inceptions

Stall inception is usually reflected as an abrupt change in the signal measured by the transducers. Lin et al. (Lin et al. 2009) developed a 1D continuous wavelet analysis tool to detect stall inception in compressors. This method can accurately locate the stall precursor in the time domain signal by observing the scale of the stall precursor. This paper will adopt the same method to capture and locate the stall precursors of each condition. Take Fig. 9 as an example. Fig. 9 showed the wavelet analysis diagram of the stall precursors under the uniform inlet condition with smooth casing. The red circle indicates that the stall precursor is measured by the CH8 sensor at the 1144.4 revolution. This result is marked in the time-domain signal analysis diagram in Figure 10a. For convenience, the subsequent analysis will only show the time-domain signal analysis diagram. Figure 10 showed the propagation of the stall precursor along the circumferential direction under the conditions of Uniform-SC and Uniform-ASCT. The gray line is the original dynamic pressure data, and the red line is the low pass filtered data. The smaller red circle shows the moment when the stall precursor occurs. The scale of the stall precursor can be seen through the enlarged image. The black arrow line represents the propagation direction of the disturbance. Since the circumferential propagation frequency of the stall precursor is generally at 70% of the rotor rotation frequency, setting the cut-off frequency of the low-pass filter to 500 Hz can obtain the main low-frequency characteristic signal.

Figure 9 Initial Position of Stall Inception through Wavelet Analysis under Uniform Inflow with Smooth Casing

As shown in Fig. 10, under Uniform-SC condition, the stall precursor that eventually induces the stall is measured by the CH8 sensor. The circumferential propagation speed of the stall precursor is 70.37% of the rotor speed. The stall precursor is a spike wave. The scale of the stall precursor occupies about 5 blade channels. Under Uniform-ASCT working condition, the stall precursor is measured by the CH4 sensor, and its circumferential propagation speed is 52.4% of the rotor speed. The scale of the stall precursor occupies about 7 blade channels. Compared with the smooth wall condition, the application of ASCT under uniform inflow significantly reduces the propagation speed of the stall precursor and increases its scale. Fig. 11 showed the propagation characteristics of the stall precursor in the circumferential direction under the conditions of DC(60)=0.90%-SC and DC(60)=0.90%-ASCT. Under DC(60)=0.90%-SC condition, the CH8 sensor measured the stall precursor that induced the final stall, and the propagation speed is 68.36% of rotor speed. The stall precursor is still a spike wave. The scale of the stall precursor occupies about 4 blade channels. In the DC(60)=0.90%-ASCT condition, the stall precursor is measured by the CH7 sensor, and the propagation speed is 51.7% of the rotor speed. The scale of the stall precursor occupies about 7 blade channels. The application of ASCT under this distortion condition can also significantly reduces the propagation speed of the stall precursor and increases its scale.

Figure 10 Stall Process under Uniform Conditions

CH8

(a) Uniform-SC

(b) Uniform-ASCT

Figure 11 Propagation Characteristics of Stall Precursors
Figure 11 Stall Process under DC(60)=0.90% Conditions

Figure 11 presented the circumferential propagation characteristics of the stall precursor under the conditions of DC(60)=4.12%-SC and DC(60)=4.12%-ASCT. Under DC(60)=4.12%-SC condition, the stall precursor is still a spike wave. The stall precursor that induces the final stall is measured by the CH7 sensor, and the propagation speed is 69.32% of rotor speed. The scale of the stall precursor occupies about 5 blade channels. In the DC(60)=4.12%-ASCT condition, the stall precursor is measured by the CH7 sensor, and the propagation speed is 54.74% of rotor speed. The scale of the stall precursor occupies about 7 blade channels. The application of ASCT greatly reduces the circumferential propagation speed of the stall precursor and increases its scale.

Figure 12 Stall Process under DC(60)=4.12% Conditions

Figure 12 showed the circumferential propagation characteristics of the stall precursor under the DC(60)=24.75%-SC and DC(60)=24.75%-ASCT conditions, respectively. Under the DC(60)=24.75%-SC condition, when the compressor throttles to a certain moment, disturbances are continuously generated in the distortion zone, and these disturbances are gradually suppressed and disappear after entering the non-distortion zone. This process lasted several revolutions. After the flow is further reduced, the distortion zone induces a disturbance with a scale of about 9 blade channels (Measured by CH8 sensor). Although the scale of this disturbance is reduced when it passes through the non-distortion zone, it has not disappeared completely. When it enters the distortion zone again, the scale increases again, and finally induces the compressor stall. The scale of the stall precursor measured by the CH2 sensor upstream of the distortion zone is about 5 blade channels, which is still a spike wave stall precursor. The propagation speed is 64.81% of the rotor speed. In the DC(60)=24.75%-ASCT condition, the intensity of the disturbance before the stall is weakened. Finally, the CH8 sensor in the center of the distortion zone measures a disturbance wave with a scale of about 9 blade channels. After it passes through the non-distortion zone, the scale gradually reduce to about 4 blade channels. When it enters the distortion zone again, the scale increases again and causes the compressor to stall. The application of ASCT under this distorted inflow hardly changes the propagation speed of the stall precursor, and the change in the scale of the stall precursor is not obvious.

For the circumferential total pressure distortion discussed above, the stall precursor always appears in the center of the distortion region or where the rotor is about to leave the distortion region (approximately within the area enclosed by the CH6-CH8 sensor). When the distortion intensity is relatively large, disturbances are continuously generated in the distortion zone, and the scale of the disturbance will decrease as it enters the non-distortion zone. When it cannot be suppressed and eliminated by the non-distortion zone, the compressor will eventually stall. In the above four inlet conditions with ASCT, the SMI is higher in the conditions where the stall precursor propagation velocity and scale change are more obvious.
Stability-enhancing Mechanism of CT

Dong et al. (Dong et al. 2015) used the time-frequency analysis method of power spectral density (PSD) to analyse the characteristics of the pre-stall static pressure signal with and without casing treatment, then explained the stability-enhancing mechanism of the casing treatment. This paper will adopt the same method, and the window function is selected as Hanning window, the number of NFFT points is set equal to the number of data points in each segment to meet the maximum frequency domain resolution. The continuous throttling signal of the CH1 sensor (plane D in Figure 2) is selected for analysis. The value of the frequency axis is the non-dimension frequency value based on the shaft frequency (40hz). The results of Dong et al. (Dong et al. 2018) indicated that the relative frequency in the range of 0.2-0.8 is the frequency related to the stall disturbance. This article shall focus on disturbance signal in this frequency band. Since the throttle valve closes at the same speed, the same time point in the figure can be approximately regarded as the same flow coefficient point. Fig.14 showed the PSD of the static pressure signal that changes along the time from the large flow condition to the small flow condition under uniform inflow with and without ASCT. The results showed that the Uniform-SC condition produced a stall precursor at about 110 seconds and grew rapidly. Under the Uniform-ASCT condition, ASCT suppressed the high peak that was supposed to occur at 110 seconds, and the high peak did not appear until further throttled to about 260 seconds, so ASCT delayed the stall. Fig.15 presented the PSD analysis results of the signal under DC(60)=0.90%-SC and DC(60)=0.90%-ASCT conditions. The DC(60)=0.90%-SC condition produced a larger peak at 100 seconds, while the DC(60)=0.90%-ASCT condition did not show a higher peak until around 250 seconds. The ASCT also delays the stall. The DC(60)=4.12%-SC condition can also see a higher amplitude peak at the time of near stall (100 seconds) from Fig.16. The DC(60)=4.12%-ASCT condition peaked at about 250 seconds. Fig.17 showed the PSD analysis results of the signal under DC(60)=24.75%-SC and DC(60)=24.75%-ASCT conditions. In the DC(60)=24.75%-SC condition, a larger value (70 seconds) is observed in the larger flow condition. In the DC(60)=24.75%-ASCT condition, the peak delay appears at nearly 230 seconds, ASCT also produced a significant stability-enhancing effect. It can also be seen from these four figures that as the distortion intensity increases, the amplitude of the disturbance signal before the stall in the flow field also tends to rise.
The above analysis is only a qualitative analysis, and the characterization of the results is not specific enough. In order to quantitatively indicate the PSD peak value, the data of the same flow condition point is compared and analysed with and without ASCT. Fig.18 showed the 2D PSD between 107 seconds and 110 seconds under Uniform-SC and Uniform-ASCT conditions (3 seconds before stall under Uniform-SC condition). The results showed that the maximum peak value of PSD is 27.1 in the Uniform-SC condition, and the maximum PSD peak value is reduced to 2.0 in the Uniform-ASCT condition. The application of ASCT can suppress the high peak PSD near the rotating stall frequency, thereby delaying the stall.

Fig.19 presented the 2D PSD between 97 seconds and 100 seconds under DC(60)=0.90%-SC and DC(60)=0.90%-ASCT conditions (3 seconds before stall under DC(60)=0.90%-SC condition). The results showed that the maximum peak value of PSD under DC(60)=0.90%-SC condition is 29.1, while under DC(60)=0.90%-ASCT condition, the maximum peak value of PSD is reduced to 5.9. Therefore, this is also the reason why the ASCT can bring a large increase in stall margin.

Fig.20 showed the 2D PSD between 97 seconds and 100 seconds under DC(60)=4.12%-SC and DC(60)=4.12%-ASCT conditions (3 seconds before stall under DC(60)=4.12%-SC condition). The results showed that the maximum peak value of PSD under DC(60)=4.12%-SC condition is 32.9, while under DC(60)=4.12%-ASCT condition, the maximum peak value of PSD is reduced to 18.4. The application of ASCT suppresses the appearance of high amplitude PSD.

Fig.21 showed the 2D PSD between 67 seconds and 70 seconds under DC(60)=24.75%-SC and DC(60)=24.75%-ASCT conditions (3 seconds before stall under DC(60)=24.75%-SC condition). The results showed that the maximum peak value of PSD under DC(60)=24.75%-SC condition is 64.7, while under DC(60)=24.75%-ASCT condition, the maximum peak value of PSD is reduced to 45.4. The application of ASCT also suppresses the emergence of amplitude PSD.

Figure 16 PSD of DC(60)=4.12% Inflow
Figure 17 PSD of DC(60)=24.75% Inflow

Figure 18 PSD of Uniform Inflow(3 seconds before stall)
Figure 19 PSD of DC(60)=0.90% Inflow(3 seconds before stall)

Figure 20 PSD of DC(60)=4.12% Inflow(3 seconds before stall)
Figure 21 PSD of DC(60)=24.75% Inflow(3 seconds before stall)
CONCLUSIONS

In this study, the stability-enhancing capability of ASCT is experimentally evaluated in an isolated-rotor axial-flow compressor under the circumferential distorted inflow. Three circumferential distortion intensities (0.90%, 4.12%, and 24.75%) are selected to conduct the steady and unsteady measurements with and without ASCT. From the results, the following conclusions can be drawn.

1. The axial slot casing treatment has produced obvious stability enhancement effects for different circumferential distortion intensity conditions, and the stall margin improvement shows a trend of first increasing and then decreasing. Among them, DC(60)=0.90%-ASCT condition has the highest SMI (43.86%); and the SMI of other conditions is between 22%-41%.

2. Under smooth casing conditions, the circumferential distorted inflow will not change the compressor stall precursor type, it is still Spike stall precursor, the propagation speed is 64%-71% of the rotor speed, and the scale occupies about 4-5 blade channels. Under the conditions where the ASCT has a better stall margin enhancement effect, the circumferential propagation speed of the stall precursor will be reduced to 50%-55% of the rotor speed, and the scale will increase to occupy about 7 blade channels.

3. The axial slot casing treatment can successfully suppress the disturbance, whose frequency is around the rotating stall frequency band under the same flow point, thereby delaying compressor stall and ensuring its anti-distortion ability. This study experimentally reveals the stability-enhancing law of ASCT under circumferential distorted inflow. From the perspective of suppressing the disturbance signal, its stability-enhancing mechanism is explained. However, ASCT has changed the evolution characteristics of stall precursors in some cases, and the details of the flow field behind this phenomenon are still unknown. In the near future, combined with computational fluid dynamics and detailed experimental data, we will further study the expansion mechanism of ASCT under distortion conditions.

NOMENCLATURE

- $\psi$ Pressure rise coefficient
- $\phi$ Flow coefficient
- $P_{s,inlet}$ Inlet static pressure
- $P_{s,outlet}$ Outlet static pressure
- $P_{t,inlet}$ Inlet total pressure
- $\rho$ Environmental density
- $N$ Shaft speed
- $U_{mid}$ Tangential velocity at the mid-span
- $V_{s,inlet}$ Inlet average velocity
- $C_{ax}$ Axial chord
- LE Leading edge
- SM Stall margin
- SMV Stall margin variation
- SMI Stall margin Improvement

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