EFFECT OF CIRCUMFERENTIAL TOTAL PRESSURE DISTORTION ON STABILITY IN AN AXIAL FLOW COMPRESSOR

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ABSTRACT
The effect of circumferential total pressure distortion on aerodynamic stability were experimentally investigated in an axial flow compressor. Different circumferential distorted inflow fields were generated with a flat-baffle installed upstream the compressor. Using a collection of time-resolved pressure transducers mounted circumferentially and along the axial chord direction, the stall route, stall inception, and end-wall flow field were captured and systematically analyzed. Results show that the stall margin is nearly linearly deteriorates as the distortion intensity increases. Although the propagating speed of stall inception is not influenced by the circumferential distorted inflow, its scale increases with the increment of the distortion intensity. In addition, the stall inception appears and develops into mature stall cell with small distortion intensity, which is similar to the uniform inflow. With strong circumferential distortion, the initiation of stall inception is affected by the inlet circumferential non-uniform. The disturbance appears downstream the circumferential distorted region because the unsteady fluctuation of tip leakage vortex is intense at the distorted region. Thereafter, it disappears at the undistorted region when the end-wall flow field recovers at undistorted region. The disturbance goes through several times of initiation-propagation-disappearance process before the stall inception formation. The rotating stall occurs when the disturbance does not disappear at the undistorted region. Through this investigation, the understanding of stall mechanism is deepened in the axial flow compressor with the circumferential distortion.

INTRODUCTION
Inlet distortion is one of major concerns of aerodynamic stability since it can directly trigger rotating stall and surge in the axial flow compressor. Among various types of inlet distortions, circumferential total pressure distortion, originated from the high incidence flight such as during taking off or crosswind, has been widely studied for several decades. Early attempts of experiments and developing analytical method were made to assess the adverse effect of circumferential distortion on stability (Hynes and Greitzer, 1987; Stenning, 1980). Base on the experimentally investigation, Reid (1969) reported some remarkable findings that the circumferential distortion played a more important role in stall margin degradation than radial distortion, and there was a critical sector angle for circumferential distortion.

As the CFD and measurement techniques develops, researcher focus on the effect of circumferential distortion on detailed flow field features and aerodynamic parameters. Zhang and Vahdati (2019) pointed out the periodicity of tip leakage vortex as the rotor enters and exits the distorted region and found that the rotating stall occurs when flow separation
is not removed at undistorted region. Liu et al. (2016) investigated the effect of inlet distortion on the performance of an axial transonic contra-rotating compressor, emphasizing the role of the detached shock wave and tip leakage flow interaction in triggering stall. Lesser and Niehuis (2014) also had similar observation that the interaction of passage shock and tip-clearance vortex leads to the vortex breakdown in a transonic compressor. Charalambous et al. (2004) claimed that the drop of the axial velocity caused by distortion increases the blade load, thereby resulting in the aerodynamic instability. In addition, the effect of circumferential distortion on stall inception was experimentally investigated (Jiang et al., 2009; Toge and Pradeep, 2017; Lin et al., 2006), in terms of stall inception type and scale, development process, and transition phenomenon.

Due to its significant adverse effect on aerodynamic stability, some researchers attempted to weaken this adverse effect of distortion, such as extending the stall margin (Dong et al., 2018; Huang and Wu, 2007) and reducing the non-uniform stator loss (Lu et al. 2019). Dong et al. (2018) used the novel casing treatment to enhance the stability margin by 6-8% with the circumferential distortion by weakening the unsteady flow perturbations and delaying the stall precursor waves. Huang and Wu (2007) applied circumferential groove casing treatment to suppress the serious blockage caused by tip leakage vortex with circumferential distortion.

The aforementioned studies mainly focus on the flow field features and stall inception with one determined circumferential distorted pattern. There is more explicit work remained to be done for the nonlinear coupling between the compressor and the circumferential distortion. Hence, the effect of circumferential distortion with different scenarios on aerodynamic stability were experimentally investigated in a low-speed, axial flow compressor.

The current paper organizes as follows: First the previous work of circumferential distortion in axial compressors is introduced. Thereafter the experimental setup and data acquisition system are presented. The circumferential total pressure distortion intensity and measured total pressure contour are performed. Then the experimental results in terms of performance lines, stall route, stall inception scale, and tip leakage vortex are presented to study how the circumferential total pressure affect the aerodynamic stability. Finally, some research conclusions are drawn.

**EXPERIMENTAL SETUP**

The experiments in current paper were carried out in an isolated-rotor axial compressor test rig of the Institute of Engineering Thermo-physics, Chinese Academy of Sciences. The rotor blade of studied compressor is modelled form a high-pressure compressor and its designed rotational speed is 2400 rpm. The detailed aerodynamic and geometrical parameters are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Isolated-Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade number</td>
<td>60</td>
</tr>
<tr>
<td>Rotor tip stagger angle/°</td>
<td>39.2</td>
</tr>
<tr>
<td>Outer diameter/mm</td>
<td>500</td>
</tr>
<tr>
<td>Rotor blade tip chord/mm</td>
<td>36.3</td>
</tr>
<tr>
<td>Rotor tip clearance/rotor tip chord, %</td>
<td>2.6</td>
</tr>
<tr>
<td>Hub-to-tip ratio</td>
<td>0.75</td>
</tr>
<tr>
<td>Design rotating speed/r·min⁻¹</td>
<td>2400</td>
</tr>
<tr>
<td>Design mass flow rate/kg·s⁻¹</td>
<td>2.9</td>
</tr>
</tbody>
</table>

The sketch of studied compressor and the data acquisition system are depicted in Figure 1. To generate the circumferential total pressure distortion, a flat-baffle is installed about 250mm upstream the rotor blade in the inlet duct with variable height (Cross section B-B). Three cases, namely case I, II, and III with different rotor blade span height (H=25%, 50%, and 75% R, R=61.6mm) are used to generate different distortion intensities. In the experiments, the throttling valve driven by a DC motor is gradually closing to model the process that the compressor is approaching the stall margin. Several typical flow conditions in the throttling process are selected to analyze the unsteady pressure signals.

The data acquisition system is divided into steady and unsteady measurement. As for steady measurement to monitor the characteristic performance, the inlet and outlet wall static pressure are measured by four static pressure taps installed 8 \( C_{ax} \) upstream of the LE and 4 \( C_{ax} \) downstream of the trailing edge (TE), respectively. A comb-probe is also located at 4 \( C_{ax} \) downstream of the TE to measure the outlet total pressure. Concerning unsteady measurement, five five-hole comb probes (Kulite XQC-062) are uniformly distributed at aerodynamic interface plane (AIP) to depict the total pressure contour after circumferential total pressure distortion. Twenty-six high frequency response transducers (Kulite XCS-190M) are mounted circumferentially and along the axial chord direction from 9.16% \( C_{ax} \) upstream of the LE to 112.5% \( C_{ax} \) of the TE. Eight are located at 15.08% \( C_{ax} \) to record the stall route and twenty-two (four rows at circumferential direction) are mounted at distorted and undistorted region to investigate the influence of circumferential total pressure distortion on the unsteady tip leakage flow. The sampling frequency for unsteady measurement is above 40 kHz, which is much higher than the blade
passing frequency (2.4 kHz) to satisfy the dynamic data acquisition requirement. In addition, the Hall sensor is installed on the shaft due to phase lock for signal processing, for example, the root-mean-square contour of pressure.

Figure 1 Experimental setup of the isolated-rotor axial compressor

RESULTS AND DISCUSSION

Prior to investigate the influence of circumferential total pressure distortion on characteristic performance, some important parameters should be defined.

**Flow coefficient $\Phi$:**

$$\Phi = \frac{V_{s,\text{inlet}}}{U_{\text{mid}}}$$  

**Inlet axial average velocity $V_{s,\text{inlet}}$:**

$$V_{s,\text{inlet}} = \sqrt{\frac{2(P_{s,\text{inlet}} - P_{s,\text{exit}})}{\rho}}$$  

**Tangential velocity at mid-span $U_{\text{mid}}$:**

$$U_{\text{mid}} = \frac{\pi DN}{60}$$  

**Pressure rise coefficient $\Psi$:**

$$\Psi = \frac{2(P_{s,\text{exit}} - P_{s,\text{inlet}})}{\rho U_{\text{mid}}^2}$$  

**Stall Margin SM:**

$$SM = \left(\frac{\Psi_{d}}{\Psi_{s}} \Phi_{d} - 1\right) \times 100\%$$  

**Stall Margin Variation SMV:**

$$SMV = SM_{\text{max}} - SM_{\text{min}}$$

where $P_{s,\text{inlet}}$ and $P_{s,\text{exit}}$ represent the inlet total and static pressure; $P_{s,\text{exit}}$ denotes the outlet static pressure; $D$, $N$, and $\rho$ denote the diameter at the mid-span, rotational speed, and environmental density; and the subscript $s$ and $d$ represent stall point and design point, respectively. The inlet Mach number at rotor blade tip region ($Ma_{\text{tip}} \approx 0.16$) is subsonic so that the flow can be viewed as incompressible. Hence, the inlet axial average velocity can be calculated by equation (3).

Three flat-baffles with 25%, 50%, and 75% span height, namely case I, II, and III, are used to simulate different distortion intensities. The DC (60), the ratio of total pressure difference between the full annulus and distorted area (worst 60-degree sector) to the inlet dynamic pressure, is adopted to assess the circumferential uniformity under the distorted
inflow. The DC (60) of case I, II, and III is calculated by measuring the total pressure contour using five probes described in experimental setup.

\[ DC(60) = \frac{\bar{P}_{\text{distortion, \theta = 60}} - \bar{P}_{\text{inlet, \theta = 60}}}{\bar{P}_{\text{inlet}}} \times 100\% \]  

(7)

where \( \bar{P}_{\text{distortion, \theta = 60}} \) is the average total pressure around the annulus at AIP; \( \bar{P}_{\text{inlet, \theta = 60}} \) represents the average total pressure within the worst 60-degree sector; and difference of \( \bar{P}_{\text{inlet}} \) and \( \bar{P}_{\text{inlet}} \) denotes the inlet dynamic pressure. According to the DC (60) definition, the distortion intensity of case I, II, and III is 0.90%, 4.12%, and 24.75%, respectively.

Figure 2 shows the total pressure distribution after different distortion at the flow coefficient of 0.45 (\( \Phi = 0.45 \)) in case II. A negative total pressure region emerges at the distorted region highlighted by red dashed line.

Figure 2 Total pressure contour with DC (60) of 4.12% (\( \Phi = 0.45 \))

Figure 3 (a) shows the performance lines under different inflow conditions. The abscissa and ordinate are flow coefficient (\( \Phi \)) and pressure rise coefficient (\( \Psi \)), respectively. The stall margin and stall margin variation (SMV) are defined to assess the stability deterioration of different distorted inflow conditions. As the distortion intensity increases, the stability of the isolated-rotor compressor deteriorates. For example, the stall margin deteriorates by 3.44% when the DC (60) is 0.90%. As the DC (60) increases to 4.12% and 24.75%, the stall margin further decreases by 11.14% and 58.32%. Combined with other experimental data obtained from the same compressor with different circumferential distortion patterns, Figure 3 (b) presents the relation between the distortion intensity and the stall margin deterioration. It can be observed that the stall margin linearly decreases as the inlet distortion is intensified.

Figure 3 Effect of different circumferential distortions on stall margin

The wavelet was a frequently used method to analyze the stall inception. Lin et al. (2006) gave the definition of 1-D wavelet transform:

\[ CWT \left( a, b, x \right) = \frac{1}{a} \int \psi_{a,b}(t) dt \]  

(8)

where \( x(t) \) represents the original casing pressure, \( a \) and \( b \) denote the scale and time parameter related to frequency and time domain, and \( \psi \) represents the mother wavelet base, like ‘Morlet’, ‘Mexican Hat’, and ‘Harr’, etc. In current study, the ‘Morlet’ wavelet base is selected to apply 1-D wavelet analysis.

Figure 4 shows the one-dimensional wavelet analysis results of unsteady casing pressure with uniform and different distorted inflow. The abscissa is the time domain; the ordinate is the frequency domain; and the contour color represents the wavelet coefficient. From Figure 4 (a), the first appearance of stall inception can be found at sensor CH8 location at
346.7 rotor revolutions with uniform inflow and then propagates at 67.7% rotational speed. After 1-2 revolutions time of propagation, the stall inception develops into the stall cell with approximate 50% rotor speed. As the distortion intensity slightly increases, the initial stall inception still appears at sensor CH8 location, and its propagation speed remain unchanged. With the further increment of distortion intensity, the unstable disturbance at distorted region (CH2) is strengthened. The instability disturbance originated from distorted region (CH2) circumferentially propagates at basically the same speed as uniform inflow (Table 2). It also can be observed that the disturbance undergoes the appearance-propagation-decay process, which always decays at the undistorted region (CH6). In addition, there are more than one disturbance in one revolution with the distortion intensity of 24.75% (marked by ① in Figure 4). Rotating stall occurs when the disturbance does not decay at the undistorted region and develops to stall cell.

**Figure 4** Effect of different circumferential distortions on stall route

(a) CH8 position

(b) CH2 position

**Figure 5** Pressure contour at different circumferential location with DC (60) of 4.12%
From above statement, the disturbance originates from the distorted region (CH2) and disappears at the undistorted region (CH6) with DC (60) of 4.12% and 24.75%. In order to clarify that the stall inception first appears downstream the distorted region rather than distorted region, take the distortion intensity of 4.12% as an example, the static pressure contours obtained by casing transducers at different circumferential locations are shown in Figure 5. It can be observed that there is a low-pressure region at the suction surface of the blade, and the it spills out of the blade passage downstream the distorted region (CH8) at 550.1 rotor revolutions (Figure 4 (c)). The low-pressure region does not spill out of the blade passage at other positions, even though the existence of strong instability at distorted region (CH2). Hence, the first stall inception under circumferential distortions is originated from the instability at distorted region, but always appears downstream the distorted region.

After the spatial and temporal identification of the stall inception with uniform and distorted inflow, the scale of the stall inception is further analyzed by one-dimensional wavelet analysis. Figure 6 shows the wavelet results of the initial stall inception with uniform and distorted inflow. The initial stall inception first appears at sensor CH8 with uniform inflow from Figure 4 (a). Hence, the wavelet result of casing pressure detected by transducer CH8 is presented in Figure 6 (a). Subfigure A is the original signal and its partial enlarged view detected by sensor CH8, and the subfigure B show the wavelet power spectrum. The abscissa of subfigure A is the time domain in unit of rotor revolution; the ordinate is the pressure signal in unit of voltage. The abscissa of subfigure B is the same as A, the ordinate is frequency domain normalized by BPF (blade passing frequency), and the contour color represents the wavelet power level. It can be evidently observed that there exists two frequency band named Band 1 and Band 2. Band 1 is the BPF, and Band 2 is the instability disturbances (0.2-0.6 BPF). The initial stall inception represented by a blue “spot” is detected at 346.7 revs highlighted by red dotted rectangle. The “spot” occupies a characteristic frequency band located at 0.267-0.533 BPF. From previous Ref. (Li et al., 2019), the characteristic frequency can show the scale information of the initial stall inception. For example, if the scale of the inception is m blade passage, the original pressure signal occupies m blade passage period in time domain; and the characteristic band is located at 1/m BPF in frequency domain. Combined with subfigure A and B in time and frequency domain, the initial stall inception under uniform inflow occupies 2~3 blade passage. Hence, the inception with uniform inflow is the short-length scale stall inception.

![Wavelet Analysis Results](image)

**Figure 6 Scale of stall inception with different inflow conditions**

Seen from Figure 6 (b), when the distortion intensity increases, the characteristic frequency band 2 is weakened while the instability disturbance energy is main focused on the distorted region (CH2), observed from Figure 4. Different from
the uniform inflow, the characteristic frequency center is approximately located at 0.133 BPF with DC (60) of 24.75% distortion. Combined with the partial enlarged view of original pressure signal from Figure 6 (b), thereby the scale of the inception occupies 7~9 blade passages. The scale of the stall inception with different distortions are listed in Table 2. Therefore, the scale of the inception will be transformed from short-length to long-length scale stall inception when the circumferential distortion intensity increases despite the similar propagation speed (Table 2).

<table>
<thead>
<tr>
<th>DC (60)</th>
<th>0</th>
<th>0.90%</th>
<th>4.12%</th>
<th>24.75%</th>
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<td>Scale</td>
<td>2~3</td>
<td>3~4</td>
<td>5~6</td>
<td>7~9</td>
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</table>

Table 2 Stall inception features with different distortion intensities

Previous research (Li, 2017) demonstrate that the root mean square contour of casing pressure can demonstrate the tip leakage flow (TLF) trajectory and its unsteady fluctuation. Figure 7 shows the $P_{rms}$ contour of the isolated-rotor compressor during the throttling process with uniform inflow. The abscissa and ordinate represent the blade passage and the axial location, respectively. The color bar indicates root mean square value of pressure normalized by the inlet dynamic pressure ($pU^2$). The deep color region represents the strong TLF unsteady fluctuation, also named unsteadiness of TLF (UTLF). In addition, the dashed arrow represents the interface of the TLF and main stream flow (MF). The $P_{rms}$ contours of several blade passages at large flow coefficient and near stall point are presented. During the throttling process, the red region appears and gradually occupies the blade passage, which means that the TLF fluctuates more intense. Additionally, the interface of TLF/MF moves forward towards the LE of the rotor blade. The compressor enters rotating stall condition when the interface of TLF/MF spills out of the passage, which corresponds to the Vo’s spike-type stall criteria (Vo et al., 2008).

After verifying the relation between characteristic UTLF and rotating stall under uniform inflow. The $P_{rms}$ contour with distortion is also analyzed to investigate the influence of circumferential total pressure distortion on the TLF trajectory and UTLF. Figure 8 depicts the $P_{rms}$ contour at distorted and undistorted region with DC (60) of 24.75% at the near stall condition ($\Phi=0.43$). The abscissa and ordinate are the same as Figure 7. Compared to the same flow coefficient condition with uniform inflow in Figure 7 (b), the TLF fluctuation intensity is obviously strengthened; and the interface of TLF/MF moves forward to the LE at the distorted region. However, the UTLF is slightly suppressed and the interface of TLF/MF moves little closer to the TE at the undistorted region.

As a result, the unsteady TLF fluctuation is enhanced, resulting in the end-wall flow field deterioration at the distorted region. Consequently, the disturbance appears downstream the distorted region and then begins to circumferentially propagates. Additionally, the disturbance decays due to the end-wall flow field recovery at the undistorted region. Rotating stall occurs when the end-wall flow field deterioration is not removed at the distorted region.

![Figure 7 Prms contour with uniform inflow](image1.png)

(a) $\Phi=0.50$ (uniform inflow)

![Figure 8 Prms contour with DC (60) of 24.75% (\Phi=0.43)](image2.png)

(b) $\Phi=0.43$ (uniform inflow)

![Figure 8 P rms contour with DC (60) of 24.75% (\Phi=0.43)](image3.png)

(c) CH6 position

(d) CH4 position
CONCLUSIONS

An experimental study is conducted to investigate the adverse effect of circumferential distortion on aerodynamic stability in a low-speed, axial flow compressor. Based on the experimental results and analysis, some conclusions can be drawn:

1. The stability margin of axial flow compressor deteriorates with circumferential total pressure distortion. As the distortion intensity increases, the stall margin degradation linearly increases.
2. Circumferential total pressure distortion affects the scale of the stall inception, but does not change the propagation speed of stall inception. As the circumferential distortion is intensified, the scale of the stall inception gradually increases.
3. The stall route with small distortion intensity is similar to the uniform inflow condition. Under strong circumferential distortion, the disturbance appears downstream the distorted region, and disappears at the undistorted region. After several times of initiation-propagation-decay process, the rotating stall occurs when the disturbance does not disappear at the undistorted region.
4. The unsteady behavior of tip leakage vortex is influenced by the circumferential distortion. At the distorted region, the unsteady fluctuation of tip leakage vortex is strong resulting in the end-wall flow field deterioration; the unsteady tip leakage vortex is weak with the recovery of end-wall flow field at the undistorted region.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Abbreviations</th>
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<tr>
<td>$C_{\text{ax}}$</td>
<td>Axial chord length</td>
<td></td>
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<tr>
<td>$p_{s,\text{inlet}}$</td>
<td>Inlet static pressure</td>
<td>$BPF$ blade passing frequency</td>
</tr>
<tr>
<td>$p_{s,\text{exit}}$</td>
<td>Outlet static pressure</td>
<td>$DI$ distortion intensity</td>
</tr>
<tr>
<td>$p_{t,\text{inlet}}$</td>
<td>Inlet total pressure</td>
<td>$LE$ leading edge</td>
</tr>
<tr>
<td>$U_{\text{mid}}$</td>
<td>Tangential velocity at the midspan</td>
<td>$MF$ main stream flow</td>
</tr>
<tr>
<td>$V_{x,\text{inlet}}$</td>
<td>Inlet average velocity</td>
<td>$PRMS$ root mean square of pressure</td>
</tr>
<tr>
<td>$\phi$</td>
<td>flow coefficient</td>
<td>$SMV$ stall margin variation</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>static-to-total pressure rise coefficient</td>
<td>$TE$ trailing edge</td>
</tr>
<tr>
<td>$\rho$</td>
<td>environment density</td>
<td>$TLF$ tip leakage flow</td>
</tr>
<tr>
<td>$UTLF$</td>
<td>unsteadiness of tip leakage flow</td>
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ACKNOWLEDGEMENTS

The authors gratefully acknowledge for the support of the National Natural Science Foundation of China with Project No. 51727810, No. 51790510 and No. 51636001, and the National Science and Technology Major Project (2017-II-0004-0017, 2017-II-0005-0018). The authors also thank the Special Fund for the Member of Youth Innovation Promotion Association of CAS (2018173). The authors are grateful to Dr. Zhihui Li, Dr. Wenqiang Zhang, and Dr. Qianfeng Zhang for the insightful discussion.

REFERENCES


Reviewer1:
1. What does the nonlinear coupling between the compressor and the circumferential distortion (page 2) mean specifically? It can be observed that the stall margin linearly decreases as the inlet distortion is intensified in the Figure 3 (b).
Response: Thanks for the question. The nonlinear coupling between the compressor and the circumferential distortion means the unsteady response of the compressor to the circumferential distortion. Although the stall margin linearly decreases as the inlet distortion is intensified from Figure 3(b), the effect of circumferential on scale of stall inception, propagating speed, and unsteady tip leakage vortices should be further investigated.

2. What are the specific criteria for determining the scale of the stall? The explanation of Combined with subfigure A and B in time and frequency domain in the paper is not clear enough.
Response: Thanks for the question. The specific criteria for determining the scale of the stall inception are as follows. First, the initial temporal and spatial location can be identified via continuous wavelet analysis, like Figure 4. Thereafter the stall inception can be determined by the center frequency of the characteristic band. If the center frequency of the characteristic band is m, the scale of the stall inception should be 1/m. Combined the original time series, the scale of the stall inception can be finally determined.

3. Why is the experimental study carried out under so many mass flow rate conditions? For example, there are at least 20 mass flow rate points for case III.
Response: Thanks for the question. The authors believe the reviewer concerns about the points in Figure 3 (a). The performance of the compressor in terms of mass flow rate and pressure rise is continuously recorded at the sampling rate of 1k Hz. Hence, there are many mass flow rate conditions and some of them are skipped.

4. In order to better reveal the influence of distortion on the compressor flow field, it is suggested to supplement the pressure contour of measuring positions 7 and 3.
Response: Thanks for the suggestion. The pressure contours of measuring positions 7 and 3 are analyzed and not presented in the paper because of the paper length limitation. The pressure contours have been added.

5. It is suggested the author should do check on the writing.
Response: Thanks for the suggestion. The authors have carefully checked the writing to improve the quality of this paper.

Reviewer2:
This paper is good in writing. Some minor modifications are advised. In the abstract part, "the stall margin is nearly linearly deteriorates" may be change to "the stall margin nearly linearly deteriorates".
Response: Thanks for the suggestion. The sentence has been modified.

Reviewer3:
The usages of English can be improved.
Response: Thanks for the suggestion. The authors have carefully checked the writing to improve the quality of this paper.