ABSTRACT

Periodic wakes not only affect the characteristics of the surface boundary layer of the blades of a compressor and cause profile losses, but also influence the vortical structures of secondary flow and lead to corresponding losses. Thus, understanding the physical mechanisms of unsteady interactions to eliminate such losses is important for improving the performance of blades of the compressor, particularly at a low Reynolds number (Re). To understand the influence of upstream wakes on the structure of the flow field and the flow mechanism in the boundary layer, this study numerically simulated a one-stage high-pressure unsteady compressor under different Reynolds numbers. The discussion focuses on the unsteady characteristics of the mechanisms of interaction between upstream wakes and the boundary layer in the high-pressure compressor. The results indicate that laminar separation was suppressed and promoted at high and low Re, respectively, resulting in corresponding changes in the losses. In addition, the influence of the wake on boundary layer transition weakened with a decrease in Re. It still caused the position of reattachment of the boundary layer to change during transition, which significantly affected the performance of the compressor.

1 INTRODUCTION

With the increase in flight altitude along with sharp decreases in atmospheric density and pressure, the Reynolds number (Re) becomes an important factor in the performance of the compressor. In general, there is a critical value of Re below which the performance of the compressor deteriorates sharply. The compressor is an important part of an aero-engine, and its performance at high altitudes directly determines the operation of the entire engine. The loss of flow in the compressor can be generally divided into three parts: profile loss, leakage flow loss, and endwall loss (Denton, 1993). Reducing these losses at low Re is key to improving the performance of the compressor. At a high altitude and a low Re, laminar separation and turbulent reattachment occur on the surface of blades of the compressor to form laminar separation bubble (LSB). Mayle (1991) observed that at a low Re, Kelvin-Helmholtz (K-H) instability occurs in the separated shear layer and spanwise vorticity is generated in it. In case of external disturbance, a transition can easily occur. Because the transition from laminar to turbulent flow occurs in the boundary separation layer, it is called separation flow-based transition. During boundary layer transition, the ability of the boundary layer to resist separation increases and the adverse pressure gradient decreases such that the turbulent reattachment of the boundary layer occurs. The loss caused by LSB on the suction surface (SS) accounts for a large part of profile loss, and includes laminar separation, transition caused by boundary layer instability, and mixing during reattachment. Therefore, the LSB in the boundary layer needs to be restrained in the design of the compressor under high-altitude flight conditions.

The periodic unsteady wakes brought about by the upstream blades are characterized by a high turbulence intensity (Tu) that propagates to the region of the boundary layer with relative motion between the rotor and the stator to affect the distributions of velocity, pressure, and shear stress along it. Meyer (1958) proposed the convection of wakes on the surfaces of blades. He simplified the interaction between upstream wakes and surfaces of the blades to a negative jet model. The disturbance velocity caused by the wake was obtained by subtracting the average velocity of the steady flow field from its instantaneous velocity. Because the disturbance velocity was directed toward the source of the upstream wake, it is called...
the negative jet model. Dong et al. (1989) carried out experiments to study the development of the boundary layer of the compressor as induced by wakes. By comparing the results with and without wakes, they found that the thicknesses of the momentum ($\theta$) of the boundary layers were similar but the processes of boundary layer transition were significantly different. However, the prevalent transition model at the time could not generate the relevant numerical simulation. With better understanding of the wake-induced boundary layer process, Halstead et al. (1997) divided the surface area of the blade into a laminar flow region, calmed region, wake-induced transitional strip, wake-induced turbulent strip, transition between wakes and turbulent between wakes. The results of measurements of the time-resolved boundary layer of the blades of the compressor and the turbine were compared with those predicted by the boundary layer code. Moreover, by changing Re, the airfoil loading, frequency, and Tu of the wake as well as their influence on each region of the boundary layer was studied. The calming region caused by the interaction between the wake and the boundary layer can restrain the separation of the latter to reduce profile losses. Meanwhile, the calming effect of the wake is an inherent phenomenon in turbomachinery, and its use does not cause structural problems. Based on the influence of the incidence on wake-induced transitions in the boundary layer, Solomon et al. (2000) claimed that the latter can be utilized by adjusting the pressure distribution on the surface of the blade. Stieger et al. (2003) focused on the interaction between wakes and boundary layer separation bubbles by conducting experiments on a flat plate, and examined the rule of variation and internal mechanism of the shear layer of the boundary layer under the influence of adverse jet flow in the wakes. In addition, the inherent mechanism of wake propagation and its unsteady flow characteristics have been studied through experimental and numerical simulations in a low-speed axial fan (Fernández, 2003) and an axial compressor (Wang, 2018), respectively.

To sum up, examining the influence of the negative jet of the wake on the boundary layer transition in the compressor can help guide compressor design and reduce flow losses at low Re. Due to the complexity of boundary layer transitions in turbomachinery, most relevant studies have focused on low-speed axial compressors or compressor cascades at a high Re. We performed numerical simulations on an axial compressor at low Re. The aim is to investigate the mechanism of influence of the wake of the inlet guide vane (IGV) on the development of the boundary layer of the downstream rotor under low Re.

2 RESEARCH OBJECT AND NUMERICAL METHOD

The high-pressure compressor of a turbofan engine was taken as the research object, and the first-stage IGV and rotor were selected for a numerical examination of the operating conditions at an altitude of 10–20 km. The number of IGVs was 50, the number of rotors was 47, and the flight Mach number of the engine was 0.75. Based on the mid-span chord length of the rotor, the Re was about $1 \times 10^5$. Table 1 shows the main geometric and aerodynamic parameters of the compressor at a 50% span. The geometry of the compressor used in this study is shown in Figure 1.

<table>
<thead>
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<th>Table 1 Main parameters of the compressor</th>
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<td>Design parameter</td>
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<tr>
<td>Number of IGVs</td>
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<td>Number of Rotors</td>
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<tr>
<td>Rotor Tip Clearance (mm)</td>
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<td>IGV Chord (mm)</td>
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<td>Rotor Chord (mm)</td>
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<td>Loading Coefficient</td>
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The three-dimensional (3D), steady or unsteady, Reynolds-averaged N-S equations were solved by ANSYS CFX based on the finite volume method and the advection scheme was discretized at a high resolution. To accurately obtain the characteristics of transition on the surface of the blade of the compressor at low Re, the SST K-ω turbulence model was used along with the $\gamma$-Re$_0$ empirical transition model based on local variables. For the case without a wake, the mixing plane was set for the rotor–stator interface to eliminate the influence of upstream wakes through circumferential averaging; and for the case of unsteady flow with a wake, a transient stator was selected for the rotor–stator interface. Time transformation and the second-order backward Euler scheme were used for the simulation of unsteady flow. AutoGrid5 was used to mesh a single passage of the compressor to save calculation resources. The distances between the inlet and the leading edge (LE) of the blade, and between the outlet and the trailing edge (TE) of the blade were two times the axial chord length. The O4H structured grid was used. To ensure the accuracy of the results for the boundary layer, the grid of the first layer of the wall was set to 0.002 mm, satisfying $Y^+ \leq 1$. The total temperature, total pressure, and flow angle were given at the inlet, and the mass flow rate of the single passage was given at the outlet for the numerical simulation. An adiabatic no-slip wall was used on the surface, and the boundary condition for rotational periodicity was set in the circumferential direction. Atmospheric temperature does not change much at an altitude of 10–20 km, and thus Re was changed by adjusting the total pressure at the inlet and flow at the outlet. Tu at the inlet was uniformly set to 5%.

The cases with 0.5-3 million nodes were computed to evaluate grid independence. As shown in Figure 2, The peak efficiency of these cases were compared. When the number of nodes was greater than 1.5 million, the change of the
efficiency was little. The grid with 1.5 million nodes satisfied the requirement of grid independence and was used for the present study. The numerical simulation and experimental results of a 1.5 stage compressor were compared in Figure 3. The little difference between the two results indicated that the accuracy of numerical method was adequate for the purposes of this study.

Figure 1 Geometry of the compressor used in this study

Figure 2 The efficiency under different number of nodes

Figure 3 The comparison between experimental and numerical results

3 RESULTS AND DISCUSSION

3.1 The effect of wake on the rotor performance under different Re

Eight cases with different Re were calculated with or without the wake. Because unsteady flow was numerically simulated, the results of cases with the wake were time-averaged. The values of Re ranged from $1 \times 10^5$ to $4 \times 10^5$. Figure 4 shows the efficiency of the rotor with and without the wake at different Re. The Re and the wake influenced efficiency. The efficiency of the rotor decreased with Re, and a reduction in its efficiency was more prominent when Re was lower. The wake had a beneficial effect on the efficiency of the rotor at high Re, but this effect weakened with decreasing Re until it was negative. To analyze flow loss at the rotor, the spanwise distribution of isentropic efficiency is shown in Figure 5. With a decrease in Re, the efficiency of the entire aspect decreased significantly instead of the hub region, showing that there was no significant change in endwall loss. A comparison of cases with and without the wake indicates that it had a significant influence on the spanwise distribution of efficiency at the minimum Re considered. Due to the wake, the efficiency above 50% span is slightly reduced, instead, the efficiency below 50% span is increased at Re=$1 \times 10^5$. 
The section of the rotor at a 50% spanwise height was selected for a more detailed examination. At low Re, the structure of the LSB kept the pressure constant. With the increase in Re, the region of constant pressure decreased and its influence on blade loading decreased. The wake-induced boundary layer transition affected the size of the separation bubble, which is an important factor affecting the loading and the performance of the rotor of the compressor. Figure 6 shows the skin friction coefficient ($C_f$) on the surface of the blade. $C_f=0$ was the position of separation and reattachment of the LSB. For results with wake, the decrease in Re caused the position of turbulent reattachment to move back and that of laminar separation to move forward. However, under different Re without the wake, the position of the boundary layer separation did not change. By comparing the results with and without the wake, it can be concluded that the wake suppressed laminar separation and promoted turbulent reattachment at high Re, but delayed turbulent reattachment at low Re. The process of wake-induced transition also indirectly affected the location of turbulent reattachment.

A 50% spanwise section was chosen to examine the characteristics of upstream wake propagation. The contours of Tu under different Re are shown in Figure 7. It represents the strength of the wake; the wake became stronger with a decrease in Re, leading to an increase in the region affected by it. Therefore, at low Re, the unsteady effect of a stronger wake was more prominent and its influence on the characteristics of the downstream rotor was more significant. Wake propagation in the passage interacted with the boundary layer, and was slower in the region near the boundary layer than in the main region of flow. The dissipation of the wake in the blade passage led to a decrease in Tu, and its structure changed with the development of the wake. Finally, the upstream wake and the wake generated by the boundary layer of the rotor mixed at the TE of the rotor, resulting in a more complex flow structure behind the rotor.
3.2 Characteristics of wake-induced boundary layer development

The influence of the wake on the development of the boundary layer at low Re cannot be ignored. The wake of the upstream vane produced a negative jet effect downstream, and two disturbance-induced vortices were formed in opposite directions, in front and behind the center of the wake. The interaction between the disturbance vortices and the boundary layer affected the separation and transition of the latter. Four cases, with Re of $1 \times 10^5$ and $4 \times 10^5$, are selected to analyze the influence of flow conditions of the boundary layer on the SS of the rotor. Figure 8 shows the contours of the nondimensional main flow velocity (U) within the boundary layer, where the dotted line shows the displacement thickness of the boundary layer. The low-velocity region in the contour represents the position and size of the LSB. The displacement-induced boundary layer began to thicken rapidly with the appearance of flow separation bubbles, which blocked the flow passage and increased loss. In addition, the boundary layer developed into turbulent flow after reattachment, and the continuous increase in its thickness led to a large loss due to turbulent viscosity dissipation. As Re decreased, the ability of the boundary to resist separation weakened and the transition process was delayed, such that the length and thickness of the separation bubble increased. It is also clear that the thickness of the boundary layer increased with a decrease in Re.
Considering the influence of the wake, its thickness decreased slightly at a high Re, and increased significantly to form an open separation bubble at low Re.

**Figure 8 The contours of U within the boundary layer under different Re**

Figure 9 shows values of θ and the shape factor (H_{12}) at different Re. H_{12} represents the velocity pattern of the boundary layer, and can reflect its separation and transition. θ represents the magnitude of the loss of momentum caused by the viscous boundary layer. There was a turning point in the curve of θ that indicated that the instability of the boundary layer had suddenly magnified, followed by a rapid increase in the loss of momentum. The reason for this phenomenon was the boundary layer transition, and the turning point represented the position of the transition. As Re decreased, the turning point of θ moved downstream and its growth rate increased after the turning point. A faster momentum growth rate indicated stronger turbulent dissipation. Compared with the case without the wake, that with a wake caused the turning point to move downstream at high Re, but the wake no longer changed the turning point and only increased the growth rate of the momentum of the boundary layer after the turning point. H_{12} represented the size of boundary layer separation. The larger H_{12} represented the more obvious boundary layer separation at low Re. By comparing with the H_{12} of the case with and without wake at low Reynolds number, it is found that the transition position before the maximum thickness of separation bubble was not affected by wake, and the wake only increased the separation size of turbulent boundary layer after transition. The difference of H_{12} was consistent with the trend of momentum thickness, and the region affected by wake at low Reynolds number was the turbulent boundary layer after transition. For high Reynolds number conditions, the change of momentum thickness indicated that wake advanced boundary layer transition. Therefore, the ability of the boundary layer to resist separation was enhanced, and the size of the boundary layer separation was reduced. There was a significant decrease of H_{12} in the entire separation bubble region.

To explore the development of the boundary layer at the wall induced by periodic wakes, three periods of passage of the rotor were selected and the phase-locked average was calculated out to obtain the space–time diagram of the SS at a 50% span. The space–time diagram of the nondimensional axial velocity (V) is shown in Figure 10. The axial velocity of the mesh of the first layer on the wall was used to represent the state of separation of the boundary layer. As there was backflow in the LSB, the position at which the boundary layer started to separate was represented by a near-wall velocity...
of zero, and the region with a negative near-wall velocity was the region of separation of the boundary layer. Tu on the wall represented the transition from laminar to turbulent flow due to instability. In addition, Tu on the wall periodically changed owing to the high-Tu fluid brought by the upstream wake. As shown in Figure 10, at high Re, the boundary layer was disturbed by the wake and the starting point of separation kept changing. At a certain time, the LSB began to appear, and the position of reattachment of the LSB kept moving downstream, followed by the starting position of separation until the LSB had completely disappeared. For the case with low Re, the position of boundary layer separation fluctuated periodically due to the wake. The sweep of the wake also caused the LSB to fall off at the tail and then move downstream with the wake. When the detached separation bubble moved to the TE of the rotor, its ability to resist separation was weak because it did not develop complete turbulent flow. Therefore, a large region of turbulent separation at the TE was formed. In case of a high Re, transition occurred closer to the LE of the blade, and the boundary layer flow was completely turbulent after reattachment. The turbulent separation was affected less by the wake and did not change with time. Instead, the turbulent separation occurred periodically due to the effect of the wake at low Re.

![Figure 9 Distributions of \( \theta \) and \( H_{12} \) under different Re](image)

![Figure 10 The space–time diagrams of V under different Re](image)

The vector diagram of the transient disturbance velocity and contour of the nondimensional transient disturbance vorticity \((\omega)\) at the same time are shown in Figure 11. There were prominent reverse vortices downstream of the wake that slowed the flow of the boundary layer fluid and generated small-scale vortices to affect the boundary layer. Converse vortices and reverse vortices appeared alternately, and accelerated and decelerated boundary layer flow, respectively, while promoting its mixing with the main flow. Figure 12 shows the transient intermittency contour at the same time used to indicate the status of flow. An intermittency of zero represents fully laminar flow and that of one represents fully turbulent flow.
The process of the transition is due to the instability of boundary layer flow. There are two main types of viscous Tollmien-Schlichting instability and inviscid K-H instability. The main phenomenon of the transition caused by K-H instability is vortex rolling, shedding, pairing and crushing, resulting in a strong mixing and momentum exchange between the boundary layer and the main flow. In general, the dominant instability type is affected by the boundary thickness, and the separation boundary layer is mainly K-H instability. In the position of the separation bubble, the region where the intermittent factor changed significantly near the main flow was caused by the K-H instability. With boundary layer reattachment, the K-H instability disappeared. As shown in Figure 12, the K-H instability induced by the wake dominated the transition process in the separated shear layer. Combined with the two figures, as the Re decreased, the reverse vortex moved upstream, leading to an expansion of the region of influence of the wake and the transition region induced by it. In addition, the intensity of disturbance vorticity decreased at low Re, resulting in the weakened influence of the derived vortex structure on the boundary layer.

4 CONCLUSIONS
This study examined the influence of the wake on the compressor and analyzed the mechanism of wake-induced boundary layer transition. The main conclusions can be summarized as follows:

(1) The influence of wakes of the IGV on the performance of the rotor varied under different Re. For Re=1×10^5, the wake reduced the endwall loss of the hub region but increased leakage flow loss and profile loss. At high Re, the wake
reduced the three kinds of losses. The LSB was an important structure of the SS boundary layer at low Re that can change the loading distribution of the blade and affect flow loss. As Re increased, the size of the LSB decreased. For the case without a wake, the position of laminar separation did not change under different Re. The wake caused the position of separation to move forward and that of reattachment to move backward at Re=1×10^5 and 2×10^5. The opposite effect of the wake was produced at Re=3×10^5 and 4×10^5.

(2) Tu in case of the wake was larger and its range was wider at lower Re. Under the influence of the wake, the thickness of the boundary layer increased significantly at Re=1×10^5. The wake caused the turning point of θ to move downstream at high Re; but at low Re, the wake no longer changed the turning point and increased only the growth rate of the boundary layer of momentum after this point. For the transient development of the boundary layer, the LSB appeared and disappeared periodically at high Re. For Re=1×10^5, the position of the boundary layer separation fluctuated periodically due to the wake. The sweep of the wake also caused the LSB to fall off at the tail and then move downstream to form a large region of turbulent separation at the TE. In addition, the K-H instability induced by the wake dominated the transition process in the separated shear layer.

NOMENCLATURE

Re  Reynolds number
LSB  Laminar separation bubble
K-H  Kelvin-Helmholtz
SS   Suction surface
Tu   Turbulence intensity
IGV  Inlet guide vane
LE   Leading edge
TE   Trailing edge
Y+  Nondimensional wall distance of first node
Cf   Skin friction coefficient
U    Nondimensional main flow velocity
θ    Momentum thickness
H_{12}  Shape factor
V    Nondimensional axial velocity
ω    Nondimensional transient disturbance vorticity

REFERENCES