Effect of blade sweep on inlet flow in axial compressor cascades

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Abstract This paper presents comparative numerical studies to investigate the effects of blade sweep on inlet flow in axial compressor cascades. A series of swept and straight cascades was modeled in order to obtain a general understanding of the inlet flow field that is induced by sweep. A computational fluid dynamics (CFD) package was used to simulate the cascades and obtain the required three-dimensional (3D) flow parameters. A circumferentially averaged method was introduced which provided the circumferential fluctuation (CF) terms in the momentum equation. A program for data reduction was conducted to obtain a circumferentially averaged flow field. The influences of the inlet flow fields of the cascades were studied and spanwise distributions of each term in the momentum equation were analyzed. The results indicate that blade sweep does affect inlet radial equilibrium. The characteristic of radial fluid transfer is changed and thus influencing the axial velocity distributions. The inlet flow field varies mainly due to the combined effect of the radial pressure gradient and the CF component. The axial velocity varies consistently with the incidence variation induced by the sweep, as observed in the previous literature. In addition, factors that might influence the radial equilibrium such as blade camber angles, solidity and the effect of the distance from the leading edge are also taken into consideration and comparatively analyzed.

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1. Introduction

Current development of aeroengine fans/compressors focuses on high loading, high efficiency, high through-flow and sufficient stall margin. Application of aerodynamic sweep in transonic compressors is an effective technique to meet high performance demands. Wennerstrom and Frost were the first to introduce sweep design in a highly loaded transonic fan in the HTFC program.1,2 Hah and Wennerstrom initially investigated backward sweep and proposed the concept of controlling three-dimensional (3D) passage shock structure using aerodynamic sweep.3 Based on this concept and the improvement of 3D computational fluid dynamics (CFD) techniques, a series of swept rotors was designed and tested.4-6 The results show that forward sweep was the only method which improved both efficiency and stall margin; in contrast, backward sweep...
obviously reduced the stall margin. Wadia et al.\(^7\) attributed the advantages of forward sweep to decreased loading at the fan tip due to shock/boundary layer interaction, lower acute suction side dihedral angle in the leading edge, and less accumulation of low momentum fluid at the blade tip. Hah et al.\(^6\) concluded that a forward sweep kept the shockwaves further back in the passage, leading to a better stall margin. Denton and Xu\(^13\,10\) indicated that a forward sweep may reduce loading near the leading edge, weaken shock wave strength and increase stall margin, while a backward sweep was beneficial for higher mass flow rate.

For subsonic axial compressors, the effect on shockwaves described above is obviously not suitable. The effects of blade sweep include the influence of secondary flow and radial redistribution despite shockwave control. Gümmer et al.\(^11\) investigated the sweep and dihedral effects in stators of axial compressors both numerically and experimentally and demonstrated that positive sweep and positive dihedral could reduce endwall losses and increase operating ranges.

In recent years, the incidence variation induced by blade sweep has been investigated and gradually understood in detail. The results of Hah et al.\(^6\) show that the relative flow angle of the forward swept blade tip at the tip was 10° smaller than the backward swept blade. The numerical results of Gallimore et al.\(^12\) show that both sweep and dihedral could affect flow incidence in subsonic compressors. Furthermore, Ramakrishna and Govardhan\(^13\) definitively indicated that a forward sweep resulted in reducing the incidence angle of a subsonic axial compressor. They proposed that mass flow rate variations were caused by variations at the incidence angles. Therefore, the alteration of inlet flow fields as the incidence angle is varied was observed and studied.

McNulty et al.\(^14\) reported a spanwise redistribution of flow with forward swept rotors, with more flow towards the tip sections. The numerical results also indicated that the forward swept blade tip would induce higher inlet axial velocity. The authors further concluded that forward sweep reduced tip loading and tip-leakage flow blockage. Vad et al.\(^15\) studied the aerodynamic effects of forward sweep of axial flow rotors. They observed increased and decreased inlet axial velocities near the tip and lower radii respectively, due to the protrusion of the forward swept blade tip into the upstream relative flow field. This leads to a decreased axial velocity at the lower radii causing increased incidence, lift, and blade performance. Passrucker et al.\(^16\) found that forward sweep of a transonic compressor rotor transferred the inlet flow towards the blade tip region which improves stability in this region. On the basis of a literature review, Vad\(^15\) summarized that the incidence variation was due to the inlet axial velocity redistributions near endwall regions.

Likewise, this paper presents a comparative numerical study of cascades to investigate the effect of blade sweep on inlet flow variation including radial fluid transfer, axial velocity redistribution and incidence variation in axial compressor cascades. In recent years, we have accomplished several highly loaded and high through-flow fan designs with swept blades\(^18\,19\) and we were conscious that inlet spanwise equilibrium may play a key role in the performance improvement affected by blade sweep. Due to the complexity of 3D flow fields, a quasi-3D method was introduced in reference\(^20\) to study the effects of circumferential fluctuation on sweep aerodynamic performances of axial fans/compressors and preliminary results were published in this previous study. The same method is adopted in this study.

2. Circumferentially averaged momentum equation

For turbomachinery, the Navier–Stokes (N–S) momentum equation in rotational cylindrical coordinates can be expressed in the axial, radial and circumferential direction, with viscous term and volume force eliminated, as follows:

\[
\begin{align*}
\frac{\partial (\rho w_{\theta}^2)}{\partial r} + \frac{\partial (\rho w_{\theta} w_{\phi})}{\partial \phi} + \frac{\partial (\rho w_{\phi} w_{\theta})}{\partial x} & = \frac{\partial}{\partial r} \left[ \rho (w_{\phi} w_{\theta} + \omega r) - \rho \frac{\partial p}{\partial r} \right] \\
\frac{\partial (\rho w_{\phi} w_{\theta})}{\partial r} + \frac{\partial (\rho w_{\phi} w_{\phi})}{\partial \phi} + \frac{\partial (\rho w_{\phi} w_{\phi})}{\partial x} & = -\rho w_{\phi} (w_{\phi} + 2 \omega r) - \rho \frac{\partial p}{\partial \phi} \\
\frac{\partial (\rho w_{\phi} w_{\phi})}{\partial r} + \frac{\partial (\rho w_{\phi} w_{\phi})}{\partial \phi} + \frac{\partial (\rho w_{\phi} w_{\phi})}{\partial x} & = - \frac{\partial p}{\partial x} \tag{1}
\end{align*}
\]

where \(\omega\) is the rotational speed, \(w\) the relative velocity, \(\rho\) the density, \(p\) the pressure and \(r, \phi\) and \(x\) the radial, circumferential and axial coordinates respectively in cylindrical coordinates. The subscript \(r, \phi,\) and \(x\) represent the radial, circumferential and axial directions, respectively. Employing a circumferential averaging operator to Eq. (1) yields

\[
\begin{align*}
\frac{\partial \bar{w}_r}{\partial r} + \frac{\partial \bar{w}_r}{\partial x} & = \frac{1}{r} \left( \bar{w}_r + \omega r \right) - \frac{1}{b \rho} \frac{\partial (b \rho \bar{w}_r)}{\partial r} + P_r + F_{Br} \\
\frac{\partial \bar{w}_\phi}{\partial r} + \frac{\partial \bar{w}_\phi}{\partial x} & = \frac{\bar{w}_\phi}{r} - 2 \omega \bar{w}_r - \frac{1}{b \rho} \frac{\partial (b \rho \bar{w}_\phi)}{\partial x} + P_\phi + F_{B\phi} \\
\frac{\partial \bar{w}_x}{\partial r} + \frac{\partial \bar{w}_x}{\partial x} & = 0 \tag{2}
\end{align*}
\]

where

\[
\begin{align*}
P_r & = - \frac{1}{rb \rho} \frac{\partial}{\partial r} \left( rb \rho \bar{w}_r \bar{w}_\phi \right) + \frac{\partial}{\partial x} \left( rb \rho \bar{w}_r \bar{w}_\phi \right) \\
P_\phi & = - \frac{1}{rb \rho} \frac{\partial}{\partial r} \left( rb \rho \bar{w}_\phi \bar{w}_\phi \right) + \frac{\partial}{\partial x} \left( rb \rho \bar{w}_\phi \bar{w}_\phi \right) \\
P_x & = - \frac{1}{rb \rho} \frac{\partial}{\partial r} \left( rb \rho \bar{w}_x \bar{w}_x \right) + \frac{\partial}{\partial x} \left( rb \rho \bar{w}_x \bar{w}_x \right) \tag{3}
\end{align*}
\]

where the superscript ‘ and ‘ represent circumferential fluctuation based on passage average and circumferential fluctuation based on density weighted average, respectively. The superscript overline and dual-overline represent passage average and density weighted average, respectively. \(F_B\) is the inviscid blade force (detailed expression please refer to reference\(^20\)). \(P\) the CF source term and \(b\) the blockage factor due to the circumferential blade thickness distribution, which is calculated by

\[
b = \frac{\varphi_s - \varphi_p}{2 \pi N} \tag{4}
\]

where \(\varphi_p - \varphi_s\) represents the circumferential blade thickness distribution, the subscript \(p\) the pressure side of blades, the subscript \(s\) the suction side of blades and \(N\) the blade number.
The blockage factor $b$ is less than 1.0 within a given stage and equal to 1.0 between stages.

The streamline curvature and total derivative of the hub-to-tip stream surface are substituted into the circumferential expression of the radial direction of Eq. (2) to obtain

\[
\frac{1}{b} \frac{\partial (bp)}{\partial r} = \frac{\overline{w}_{r}}{r} + \frac{\overline{w}_{m}}{r_{c}} \cos \sigma - \frac{\overline{w}_{m}}{m} \sin \sigma \frac{\partial \overline{w}_{m}}{\partial m} + P_{r} + F_{Br}
\]

where $\sigma$ is the slope angle, i.e., the angle between the streamline and axial direction, $r_{c}$ the local radius of curvature of the streamline, $v$ the velocity of the absolute coordinate system and $m$ the streamwise direction in meridional plane.

### 3. Computational methodology

#### 3.1. Cascades model

Stationary straight and non-radially stacked cascades were selected for the computational models in this study, in order to concentrate solely on the effect induced by the sweep and eliminate other factors which may be due to design parameters. The blade profile is identical at every spanwise section and only the chordwise locations are different in each cascade. A circular arc was adopted for the style of blade airfoil camber. The thickness distribution is the same as the MAN GHH 1-S1 controlled diffusion airfoil. Other specific parameters of the cascades are listed in Table 1. It is known that the endwall boundary viscosity can affect the flow by up to 20% of the span. Due to blockage, the radial flow occurs along the span. In order to eliminate or weaken the endwall viscous effect at mid-span to enable the effects of blade sweep including radial fluid transfer and distributions of inlet flow to be studied in isolation, an aspect ratio of 6.0 was set to minimize the influence of viscosity at mid-span.

#### 3.2. Sweep configurations

Different definitions of sweep have been adopted in the literature. In this paper, we used the definition known as “true sweep” as described by Denton and Xu or “tip chordline sweep” as defined by Ramakrishna and Govardhan, i.e., the sweep was defined as moving airfoil sections along the chord line (see Fig. 1 and $\theta$ is the blade camber angle). According to Denton and Xu, defining sweep in this form does not introduce any spanwise blade force, whereas lean (moving the blade sections perpendicular to the chord line) does introduce the influences of blade forces.

The sweep angle was defined as the angle between the leading edge of the cascade and the radial direction in the chordwise direction. When a higher span section was moved in the upstream direction relative to the lower section, it was defined as forward sweep. A move in the opposite direction was defined as backward sweep. For the specific cases in this study, each spanwise section had a unique sweep angle, i.e., a stacking line without bend points was applied, thus the leading edge of the cascade cast a straight line to the meridional plane. In order to investigate the effect of aerodynamic sweep on flow variation, in particular radial fluid transfer at the inlet, forward swept (FS) and backward swept (BS) blades, as well as the straight blade (ST), were modeled for comparison. Specifically, seven cases in total including three forward swept blades, three backward swept blades and one radially stacked blade were used in the calculations. Spanwise constant sweep angles of $10^\circ$, $20^\circ$ and $30^\circ$ were set for the FS and BS cases, respectively. Fig. 2 illustrates the meridional view of the $30^\circ$ forward and backward swept and unswept cases.

<table>
<thead>
<tr>
<th>Table 1 Specific parameters of cascades.</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Blade camber angle $\theta$ (°)</td>
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<tr>
<td>Chord length (mm)</td>
</tr>
<tr>
<td>Blade geometric inlet angle $\beta_{1k}$ (°)</td>
</tr>
<tr>
<td>Radius of leading edge/chord (%)</td>
</tr>
<tr>
<td>Radius of trailing edge/chord (%)</td>
</tr>
<tr>
<td>Maximum thickness/chord (%)</td>
</tr>
<tr>
<td>Maximum thickness location/chord (%)</td>
</tr>
<tr>
<td>Aspect ratio of cascades</td>
</tr>
<tr>
<td>Solidity</td>
</tr>
</tbody>
</table>

Fig. 1 Definition of sweep.

Fig. 2 Sketch of swept cases in meridional view.
3.3. CFD method

All calculations were performed with a finite-volume based Reynolds-Averaged Navier–Stokes solver FINE Turbo by NUMECA International. A multi-block structured grid of about 1,376,000 mesh points without tip clearance was adopted. An H-type grid was used for both the inlet and outlet block, and an O-type grid was employed for the blade passage block. The length of the inlet domain is approximately 1.5 times as long as the chord line and the outlet domain is twice as long as the chord line at mid-span. The Spalart–Allmaras turbulence model was selected for the calculations. Total pressure, total temperature and direction of flow were fixed at the inlet boundary. A uniform inlet boundary condition was adopted for every computational case. An adiabatic non-slip-ping condition was applied for solid wall boundaries. The inlet flow angle was set to $57^\circ$ which was equal to the inlet metal angle, so as to ensure that the nominal incidence was zero. At the outlet boundary, static pressure was adjusted to ensure a certain averaged inlet Mach number, which was set to 0.156 in all cases. Fig. 3 shows the grid of the computational domains for the straight blade.

4. Results and discussion

Based on the 3D flow fields, a program for circumferential data reduction was carried out to obtain the required variables to calculate the blade forces, CF terms and other terms in the momentum equations. Every term is dimensionless, and the total pressure, the density and the difference between the upper and lower radius at the domain inlet were selected for reference pressure, density and length. The radial equilibrium equation and radial fluid transfer were carefully studied due to their importance; the circumferential equation and incidence variation were discussed in detail in reference. All comparisons were performed at the same uniform inlet boundary condition of the flow angle (i.e. nominal incidence) and Mach number. The CFD data was measured at the same axial location for every case, which was the position with a distance from the leading edge of 2.5% of the chord length in front of the blade inlet planes.

4.1. Comparison of blade sweep on inlet radial equilibrium

Fig. 4 shows the spanwise distributions of each individual term in the momentum equation (Eq. (5)) from 10% of the span to 90% of the span. The regions below 10% of the span and above 90% of the span are omitted, due to the evident viscous effect. For Eq. (5), the GPR ($\frac{\partial p}{\partial r}$), CMR ($-\frac{\bar{\rho} v u}{r} \cos \sigma/r_c$) and DMR ($-\frac{\bar{\rho} v u}{r} \sin \sigma/r_c$) terms represent the centrifugal force resulting from pitchwise flow, the radial pressure gradient; the CFT ($\frac{\bar{\rho} v u}{r}$), CMR ($-\frac{\bar{\rho} v u}{r} \cos \sigma/r_c$) and DMR ($-\frac{\bar{\rho} v u}{r} \sin \sigma/r_c$) terms represent the centrifugal force resulting from pitchwise flow, the radial pressure gradient; and the radial pressure gradient at the domain inlet was 0.156.
component of the stream curvature in the meridional plane and the radial component of the stream acceleration in the meridional plane, respectively. The $P_r$ term is radial component of the CF terms.

As shown in the figures, the magnitudes of both CFT and DMR are far lower than the others; therefore these two terms can be totally neglected in the equilibrium analysis. For the $P_r$ term, the spanwise distribution is uniform except at the endwall areas. Except for one particular case, values at different spans are almost identical. Additionally, the differences between the adjacent curves are also nearly identical, which suggests that the value of $P_r$ linearly varies as a function of the sweep angle. The endwall viscous effect is more obvious for the pressure gradient distribution and at least 25% of the span is influenced. The values near the mid-span are uniform but not completely identical along the span, which is directly reflected in the baseline case. Owing to the impact of the viscosity of the hub and casing, the velocities near the endwall are lower than the free stream, resulting in a radial pressure gradient and a radial fluid transfer. However the value at mid-span is zero due to symmetry. Note that the magnitude of GPR of a particular case is greater than the corresponding magnitude of $P_r$. In addition, the combination of these two terms dominates the gross pressure gradient, as shown in Fig. 5.

The distribution of the value of GPR-$P_r$ along the span has a similar trend to CMR, that is, the variation of radial pressure gradient induces the alteration of the centrifugal force resulting from stream curvature. Regardless of the endwall areas, Fig. 5 indicates that the alteration of inlet flow field is attributed to increasing the sweep angle relative to the straight blade in both directions. However, it is observed that the variation induced by the sweep is not infinite, as the change is small from FS20° to FS30° and from BS20° to BS30°. In other words, performance improvements cannot be continually achieved by increasing the extent of the sweep. In fact, the aerodynamic sweep technique applied in fan/rotor design generally reaches a compromise between aerodynamic improvement and structural stability in practical engineering.

Fig. 6 shows the spanwise distributions of radial and axial velocity, respectively. For the straight blade, the fluid in the inlet area flows towards the mid-span because of the viscous blockage near the hub and casing and reaches a balance at mid-span due to symmetry. For the forward swept blades, the fluid at the inlet has a tendency to flow outwards and this trend is stronger as the sweep angle increases. As discussed in the preceding section, forward swept blades cause a variation in the gross radial gradient resulting in an additional outward velocity component in comparison with the straight blade. Backward swept blades show a reverse trend due to the opposite direction of the radial gradient. The phenomenon of radial fluid transfer is a direct result of the change in radial equilibrium, which is
caused by the sweep. The axial velocity distribution is consistent with the radial velocity. For a forward sweep, the inlet flow deflects outwards so that more mass flow can be observed at higher radii. The larger mass flow provides the larger axial velocity, and undoubtedly the velocity is smaller at lower radii as a result of the same inlet amount of mass flow with the baseline blade. Such flow effect induced by forward sweep has also been described with similar results in Ref. 17.

In summary, the aerodynamic sweep strongly influences the inlet radial equilibrium, inducing a variation in the radial component of the centrifugal force, with a streamline curvature term (CMR) dependent on the radial and axial velocities. This section provides a quantitative analysis on radial equilibrium.

Fig. 7 plots the flow angle distribution along the spans of ST, BS10°, BS20° and BS30°, respectively. At the tip sections, the increased flow angles of the backward swept blades indicate larger incidence angles as a result of the identical stagger. At the same span, the incidence increases as the sweep angle is raised according to the axial velocity referring to the velocity triangles. At the hub sections, the incidence pattern is opposite to that at the tip, which fully predicts the expected result of a forward sweep, due to symmetry between a hub with backward sweep and a casing with forward sweep. Note that the portion with locally decreased incidence is far smaller than that with locally increased incidence. It may be that this portion is related to the specific cascades, nevertheless it can be inferred that the endwall region constituted by the swept leading edge and the hub/casing boundary causes the difference. Specifically, for a tip region with backward sweep, the leading edge forms an acute angle with the casing line in the meridional plane, while an obtuse angle is formed for the hub region with backward sweep. Therefore the narrow bound will cause a stronger effect within the majority of the spanwise range (i.e., 80% of the span), while the wide border will have a lesser influence. In other words, the incidence variation is a result of the combined effect of sweep and the endwall.

4.2. Comparison of different blade loading

A comparison of the effect of blade loading was performed in this section. Two cases with a camber angle of 30° and 15° were modeled for both FS20° and BS20°. Other parameters including inlet Mach number, inlet metal angle, inlet flow angle etc. were identical.

Fig. 8 shows the comparison of the spanwise distributions of GPR, $P_r$, GPR-$P_r$ and CMR. As shown, the absolute values of GPR and $P_r$ increase as the camber angle is raised from 15° to 30°, indicating that an increased camber angle will amplify the effects of sweep on inlet flow variation.

The distributions of CMR and the composite radial gradient (i.e. GPR-$P_r$) confirm the previously inferred tendency. It should also be noted that the radial velocity when the camber is 30° is greater than when the camber is 15°. A comparison of the distribution of axial velocity is shown in Fig. 9.

Fig. 8  Comparison of spanwise distributions of GPR, $P_r$, GPR-$P_r$ and CMR at different camber angles.
Fig. 9  Comparison of spanwise distributions of radial and axial velocity at different camber angles.

Fig. 10  Comparison of spanwise distributions of GPR, $P_r$ and GPR-$P_r$ at different solidity values.

Fig. 11  Comparison of normalized distance from leading edge in different swept cases.
span, the values are identical; however, the difference increases along the span towards the endwall. For the forward swept blade in particular, the increased blade loading causes an increase in the axial velocity near the casing and a decrease near the hub region. Furthermore, it can be inferred that the incidence angles near the tip of forward swept blades decrease when the blade camber angle is raised from 15° to 30° according to this figure. Thus, it can be concluded that the effect of sweep on inlet flow variation is more sensitive to higher loading blades.

4.3. Comparison of different solidity values

A comparison of the effect of solidity is performed in this section. Solidity values of 1.18, 1.47 and 1.60 for forward swept cascades were modeled for comparison. The variation of solidity relies on the change in pitchwise distance of the adjacent blades. The chord length of cascades is fixed to 100 mm to be identical to the reference cascade and to ensure that solidity is the only varying parameter.

Fig. 10 shows a comparison between different cases. The results indicate that solidity causes a variation of the distributions of GPR, $P_r$, and GPR-P$_r$. As is shown, increasing solidity increases the magnitude of $P_r$, indicating that the circumferential fluctuation is strengthened as the pitchwise distance is reduced. It is inferred that the difference is due to the circumferential pressure gradient. As the pitchwise length is reduced, the average circumferential pressure gradient increases, since the circumferential pressure difference is generally constant. This increases the absolute value of GPR and $P_r$. From the perspective of 3D flow, solidity influences the cascade flow and is an important parameter in compressor design. However, since the distributions of GPR-P$_r$ at different solidities converge from at least 30% span to 70% span, the solidity has little influence on radial equilibrium from the perspective of circumferentially averaged flow.

4.4. Influence of distance from leading edge

The preceding discussions are based on CFD data which is measured at an upstream location very close to the blade leading edge. Fig. 11 plots the values of GPR and $P_r$ against the distance from the leading edge at mid-span.

The values of GPR and $P_r$ are normalized by the corresponding parameters at the point where the distance is 2.5% of the chord length from the leading edge with 20° backward sweep. The distances are additionally normalized by the chord length, as shown in Fig. 11. GPR$_0$ and $P_{r0}$ represent the corresponding reference values of GPR and $P_r$, respectively. The values of GPR, as well as $P_r$, decline rapidly once the distance is extended slightly away from the leading edge up to a distance of 10% of the chord length from the leading edge. From 15% on, the drop slows down until it almost remains unchanged at a distance of 30%. The $P_r$ values drop to zero at far field, while the GPR values stay at a certain level due to the restriction of upper and lower boundaries. This indicates that the effect of sweep on inlet flow variation does exist and this effect grows with the extent of sweep.

In the past, the inlet flow field was treated as axisymmetric in both the streamline curvature method and the circumferentially averaged method, which serve as both design and analysis methods. It is appropriate when blades are radially stacked due to the uniform flow fields in front of the leading edge. However, it is no longer suitable when sweep techniques are applied because of the induced circumferential fluctuation. The upstream flow is no longer uniform and it is believed that this is caused in part by the variation of the radial equilibrium characteristic. Therefore it is necessary to model the CF effect at the blade inlet in quasi-3D methods, in order to acquire accurate inlet flow fields. For a compressor design, the selection of incidence is one of the most important factors. This paper attempts to investigate the flow mechanism on blade sweep and support for modeling for quasi-3D methods.

5. Summary and conclusions

Comparative numerical studies have been carried out on cascades, aimed at investigating the effect of blade sweep on inlet flow variation in axial compressor cascades. This work contributes toward an explanation of the inlet flow field alteration related to the aerodynamic behavior of swept blades. Although this work is based on an inviscid assumption, the flow mechanism is quite accurately conveyed because viscous effects are secondary in free stream flows and pressure equilibrium mainly dominates the flows. Denton and Xu consider that in many cases the understanding of inviscid flow is sufficient to exploit the 3D effects such as sweep and lean. The conclusions are summarized as follows.

1. The studies presented indicate that sweep causes evident alteration to inlet flow fields through a comparison of forward swept, backward swept and radially stacked blades. The radial pressure gradient, as well as the radial component of CF terms, varies when sweep is applied to the blades. Additionally, the variations of flow parameters with streamline curvature are observed. The spanwise distribution varies according to GPR minus $P_r$, indicating that the inlet flow variation is a result of a combined effect of the radial pressure gradient and the radial component of CF terms.

2. Radial fluid transfer occurs due to the variation of radial equilibrium at the blade inlet. Outward flow induced by forward sweep transfers more fluids to tip region, and consequently the axial velocity is increased due to the combined effects of radial fluid transfer and endwall boundary. Similarly, backward sweep shows the opposite effect. Furthermore, the decrease of flow incidence is directly related to the increase of axial velocity due to inlet flow triangles. As a consequence, blade performances are dominated by incidence characteristic.

3. Indications show that the inlet flow spanwise redistribution is sensitive to blade loading. As the blade loading is increased, the effect of sweep is amplified at the blade inlet and a larger radial velocity is observed. However, solidity of cascades is demonstrated to be less important to the aerodynamic effect for inlets deriving from sweep. This provides guidelines for better compressor designs that can take advantage of sweep techniques.

4. The effect of sweep on the inlet flow declines rapidly with the enhancement of the distance from the leading edge, suggesting that the effect is restricted in a small area in the upstream of the blades.
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References


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