Computational Design and Experimental Evaluation of Using a Leading Edge Fillet on a Gas Turbine Vane

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Introduction

Modern gas turbine engines are designed to have products exiting the combustor at temperatures well above the melting temperature of the first vane in the downstream turbine. If these temperatures are not properly accounted for, the additional thermal load experienced by the vane significantly reduces the vane life. The leading edge and endwall platforms of the vanes are areas where the thermal loads are the highest for two reasons. First, because the platform is affected by secondary flows it experiences increased heat transfer coefficients. Second, the vortical flows increase the transport of relatively hotter fluid from the mid-span toward the endwall.

Previous studies have shown that regions on the platform having the highest heat transfer coefficients correlate with regions having the most intense vortex action. Langston [1] was the first to illustrate a secondary flow model for an approaching two-dimensional boundary layer along the endwall. This flow model agrees well with the flow field that has been measured for the vane used in our study (Kang et al. [2], and Kang and Thole [3]). The secondary flows include a leading edge horseshoe vortex that splits into a suction side leg and a pressure side leg with the pressure side leg becoming indistinguishable as it quickly merges with the passage vortex. It is not surprising then that the leading edge endwall juncture is where the highest heat transfer occurs (Kang et al. [2]).

The focus of the study reported in this paper is to evaluate a relatively simple modification that can be made to the leading edge-endwall juncture with the specific goal of reducing the horseshoe vortex. The specific objectives of this paper are two-fold. The first objective is to determine whether placing a fillet in the endwall juncture region will reduce (or eliminate) the horseshoe vortex and then to determine the impact of that reduction on the development of the downstream passage vortex. The second objective is to determine the feasibility of using CFD to design a fillet by comparing computational predictions and experimental measurements.

Previous Studies

To create a method of horseshoe vortex reduction/elimination, it is first necessary to understand the reason for the formation of the vortex. Kubendran et al. [4], Eckerle and Langston [5], Pierce and Shin [6], and Praisner et al. [7] have all provided similar explanations. When an incoming boundary layer approaches a bluff body a total pressure gradient forms along the span direction (radial direction in a turbine) at the leading edge. The reason for this gradient is because as the velocity decreases toward the wall a lower total pressure occurs near the wall when considering the static pressure to be constant normal to the wall (typical boundary layer assumption). As the flow stagnates, the total pressure profile then becomes a static pressure gradient along the span. This spanwise pressure gradient causes the boundary layer fluid to be driven towards the endwall. As the flow turns back upstream, it rolls into a vortex or a system of vortices that wrap around the body and proceed well downstream.

There are few studies in the open literature reporting methods to reduce or eliminate the horseshoe vortex with all of these studies using symmetric airfoils except for Sauer et al. [13] who studied an asymmetric airfoil (turbine blade). Many of these past studies were directed toward wing/body intersections and submarine coming tower applications. Table 1 summarizes past fillet studies along with their respective fillet geometries and sizes based on...
These studies will be highlighted in the next paragraphs.

Pierce et al. [6] compared five different fillet geometries including two different sizes of circular corner fillets, an elliptical corner fillet, an upstream flow fence, and a large leading edge triangular fillet. Their results showed that only the leading edge triangular fillet successfully reduced the leading edge vortex. Flow field measurements for this geometry not only indicated a reduction in the vortex, but also a reduction of the total turbulent kinetic energy by approximately 20 percent.

Kubendran and Harvey [8] studied three fillet geometries including two fillets in which the height was linearly varying with streamwise distance and one fillet in which the height was a polynomial function (curved fillet). They reported that all three geometries were effective at reducing the horseshoe vortex. The authors also performed the experiments with the airfoil at different angles of attack reporting that at moderate angles of attack the fillets still reduced the overall drag. When a larger fillet was used at higher angle of attack, the flow downstream of the wing was adversely affected. These results led the authors to conclude that an optimum fillet size may be required to achieve an overall improvement in the flow when operating at an angle of attack.

Sung and Lin [9] performed a numerical investigation to determine how the size of fillets, when placed on both the leading and trailing edges of the airfoil, affected its performance. Their results indicated that a leading edge fillet needed to have a length longer than or equal to the height of the fillet to be effective. They reasoned that these proportions were required since the distance between the vortex core and the leading edge of the airfoil, in absence of a fillet, was greater than the distance between the vortex core and the endwall.

Sung et al. [10] performed similar computations in conjunction with experimental measurements on two separate airfoils with the same fairing geometry. The airfoils used were NACA 0020 and NACA 0012 airfoils, with the NACA 0020 having a more blunt leading edge and thus a stronger horseshoe vortex in the absence of the fairing. The fillet geometry used was the most effective one studied by Sung and Lin [9], which was one boundary layer thickness high and two boundary layer thicknesses long. From their results they inferred that one fillet geometry was effective in reducing the horseshoe vortex for two very different airfoils.

Devenport et al. [11] performed measurements to evaluate the effectiveness of a constant radius fillet around the entire airfoil. The close resemblance of the numerical simulations using the RNG-κ ω turbulence model with nonequilibrium wall functions was used for the turbulence model. The effectiveness of the numerical simulations using the RNG-κ ω turbulence model with nonequilibrium wall functions by Hermanson and Thole [16] and experimental measurements performed by Kang and Thole [3] on the same turbine vane geometry validated the use of these models for the fillet simulations. Each case took approximately 96 h of computing timing time on four processors.

Devenport et al. [14] performed measurements to evaluate the effectiveness of a constant radius fillet around the entire airfoil and found it to be ineffective for two different inlet boundary layers thicknesses. In a later study, Devenport et al. [11] performed measurements on the same airfoil using what they termed a strake (curved fillet). Their results indicated that the leading edge separation associated with a horseshoe vortex was not present. Velocity measurements, however, indicated that the addition of the strake did not totally eliminate the formation of vortices in the juncture. The authors hypothesized that the vortices seen downstream of the airfoil formed off the symmetry plane. The results did show that the vortex legs were much smaller and closer together indicating a weaker vortex. Two boundary layer thicknesses were studied using the same fillet with the results being surprisingly similar for both cases. These results indicate that boundary layer thickness may not be the correct scaling parameter.

Sauer et al. [13] studied the effects of various sized leading edge “bulbs.” The objective of the study was to intensify the suction side branch of the horseshoe vortex and, through an interaction of the stronger suction side branch with the passage vortex, weaken the passage vortex. While Sauer et al. did not make measurements inside the passage or at the leading edge, their detailed total pressure field measurements at the exit of the cascade indicated an interaction between the suction and passage vortices and ultimately a 50 percent reduction in aerodynamic losses for their best bulb design. They found that the best geometry was an asymmetric bulb that had a pronounced suction side and a less extended pressure side. Sauer et al. also found that their CFD results agreed qualitatively to their measurements.

As can be seen in the above review, leading edge fillets are promising for reducing the horseshoe vortex formed at the leading edge of a blunt body such as an airfoil. While there have been some detailed measurements at the exit of the airfoil passage indicating a change to the total pressure profile, there is currently no experimental data to verify the effectiveness of the fillet at the leading edge of a turbine vane. In addition, there has not been any comparison between experimental results and CFD predictions in this region.

### Table 1: Previous studies using fillets

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Geometries</th>
<th>Fillet Length</th>
<th>Fillet Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kubendran and Harvey</td>
<td>curved and linear fillets</td>
<td>0.148, 0.288</td>
<td>0.145</td>
</tr>
<tr>
<td>Kubendran, et al.</td>
<td>curved and linear fillets</td>
<td>3.75, 7.46</td>
<td>3.76</td>
</tr>
<tr>
<td>Pierce, et al. [6]</td>
<td>triangular/corner fillet</td>
<td>0.786</td>
<td>2.336</td>
</tr>
<tr>
<td>Sung and Lin [9]</td>
<td>linear fillet</td>
<td>16, 1.55, 25</td>
<td>16, 1.55</td>
</tr>
<tr>
<td>Sung, et al. [10]</td>
<td>linear fillet</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>Bernstein and Hamid</td>
<td>asymmetric fillet</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>Sauer et al. [13]</td>
<td>bulb on a blade</td>
<td>1.76</td>
<td>no data</td>
</tr>
</tbody>
</table>
vane is symmetric about its midspan, a symmetry boundary condition was applied at the midspan to minimize the size of the domain.

The details of the recirculating wind tunnel and design of the stator vane test section used in this study have been documented thoroughly in a number of previous studies including Kang et al. [2], Kang and Thole [3], and Radomsky and Thole [17,18]. To better achieve detailed flow-field measurements, the stator vane was scaled up by a factor of nine. Figure 1 depicts the corner test section of the wind tunnel as well as a description of the vane. The test section contained a central vane and two adjacent vane leading edges. These leading edges were installed to ensure proper modeling of the passage and secondary flows within the cascade. Attached to the outside leading edge was an adjustable flexible wall. The flexible wall was adjusted so that the geometry of the adjacent vane was matched. Downstream of where the adjacent vane ends, the flexible wall was adjusted so that the pressure distribution on the central vane was matched to a two-dimensional, inviscid, periodic CFD prediction for the vane at low speeds.

The inlet flow quality to the cascade has been previously reported by Kang et al. [2]. Particular care has been taken to insure equal flowrates in both passages to within 1 percent. The inlet turbulence for this study was 0.6 percent. The incident velocity was set to 5.85 m/s to match the inlet Reynolds number ($Re_{in} = 2.3 \times 10^5$) of that of the engine under operating conditions at an altitude of 9.1 km.

Figure 2 shows the position of the flow field planes measured and the nomenclature used in this study. In each plane the $u$, $v$, and $w$ components of the velocity were measured using a laser Doppler velocimeter, where these components were the local velocities defined by the measurement planes. Note that these planes, except for the leading edge plane, were orthogonal to the vane surface. Orthogonal planes allowed the secondary flows to be analyzed. The planes were defined by finding a tangent line on the vane where the measurements were desired and creating a line normal to the tangent.

Since measurements were made on both the top and bottom endwalls, boundary layer measurements were characterized on both endwalls to ensure similarity of the incoming flow. Figure 3 shows the boundary layer measurements made one chord upstream of the vane leading edge and Table 2 summarizes the boundary layer characteristics. The figure shows the results plotted against the bottom boundary layer result of Kang et al. [2] and Spalding’s law (White [19]) where the constants are 5.0 and 0.41. As can be seen, the top and bottom boundary layers exhibit the same boundary layer characteristics and closely match those measured by Kang et al. [3] and Kang and Thole [2]. Table 2 gives the boundary layer characteristics for the filleted and unfilleted experimental results. This agreement to the previous results is important since comparisons will be made to those unfilleted vane results.

A two-component, back-scatter, fiber optic laser Doppler velocimetry (LDV) system was used to measure the mean and turbulent flow fields in the turbine vane passage. The LDV system consisted of a 5W Coherent laser along with a TSI model 9201 Colorburst beam separator. A two-component laser probe, TSI model 9832, was used to transmit the laser beams and receive the scattered light. A fiber optic cable carried the velocity data to a TSI model IFA 755 Digital Burst Correlator where it was pro-

<table>
<thead>
<tr>
<th>Plane</th>
<th>y/C</th>
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<tbody>
<tr>
<td>SP</td>
<td>0.05</td>
</tr>
<tr>
<td>PS0</td>
<td>0.16</td>
</tr>
<tr>
<td>PS1</td>
<td>0.21</td>
</tr>
<tr>
<td>SS1</td>
<td>0.35</td>
</tr>
<tr>
<td>SS2</td>
<td>0.45</td>
</tr>
</tbody>
</table>

**Fig. 1 Schematic of the stator vane cascade**

**Fig. 2 Measurement and computational plane locations**

**Fig. 3 Boundary layer profiles measured upstream of vane**

**Table 2 Approaching boundary layer characteristics**

<table>
<thead>
<tr>
<th>$Re_{in}$</th>
<th>Top (with fillet)</th>
<th>Bottom (with fillet)</th>
<th>Top (without fillet)</th>
<th>Bottom (without fillet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{99}$ (cm)</td>
<td>5.3</td>
<td>5.3</td>
<td>5</td>
<td>4.8</td>
</tr>
<tr>
<td>$\delta$ (cm)</td>
<td>0.89</td>
<td>1.06</td>
<td>1.06</td>
<td>0.92</td>
</tr>
<tr>
<td>$\theta$ (mm)</td>
<td>6.11</td>
<td>7.22</td>
<td>7.37</td>
<td>6.2</td>
</tr>
<tr>
<td>$H$</td>
<td>1.46</td>
<td>1.48</td>
<td>1.5</td>
<td>1.48</td>
</tr>
<tr>
<td>$Re_{in}$</td>
<td>2874</td>
<td>3401</td>
<td>3340</td>
<td>2960</td>
</tr>
<tr>
<td>$U$ (m/s)</td>
<td>6.29</td>
<td>6.27</td>
<td>7.33</td>
<td>7.45</td>
</tr>
</tbody>
</table>
cessed. The Find™ software by TSI corrected the velocity for bias effects using residence time weighting. To map out the threedimensional flowfield within the measurement planes, each location was measured twice with the two-component LDV. From a statistical analysis, we determined that 10,000 samples were needed for each component of the velocity. To allow optical access to measure the u and v components of velocity, a glass cover was placed over the vane test section. The w-component of the velocity was measured through glass windows located on the side of the test section.

Uncertainty estimates were calculated on the methods described by Moffat [20] with estimates of derived values being calculated using the sequential perturbation method. A 95 percent confidence interval was used for the precision uncertainty estimates. The uncertainties are given in Table 3 for each of the values reported in this paper.

### Fillet Design and Fabrication

Nine different fillets were simulated computationally prior to experimentally testing a final fillet design. The CFD results from each of the fillets were assessed in terms of the effectiveness each had on the reduction of the horseshoe vortex as compared to the baseline CFD simulations for the unfilleted vane. The design of the fillet was first guided by the criteria set by Sung and Lin [9] in which the length of the fillet be greater than the height. A review of the literature on various fillet geometries for symmetric airfoils suggested that the fillet be at least one boundary layer thickness in height. Figure 4 presents the characteristics of the seven fillet designs computationally simulated (Zess and Thole [21]).

The initial fillet design was based on a 1/7th power law profile, similar to the velocity profile for a turbulent boundary layer. This profile represents the shape of the fillet approaching the stagnation plane, as illustrated in Fig. 4(a). This design indicated no reduction in the horseshoe vortex. Since a 1/4 power law profile also resulted in no reduction of the horseshoe vortex, the power law profile fillets were abandoned. Instead, a symmetric fillet about the stagnation line was designed to have a linear slope approaching the stagnation. After multiple trials, a fillet 1.6 high and 2Δ long was found to be effective at eliminating the horseshoe vortex. Further analysis of the flow around the fillet indicated that the flow was separating off the suction side of the fillet, producing yet another vortex. To eliminate the separation off the suction side of the fillet, the geometry of only the suction side was modified to eliminate the separation. The final fillet design was asymmetric having dimensions 1.6 high and 2Δ long. The final fillet design is illustrated in Fig. 4(b).

The asymmetric fillet design was then constructed and placed within the low-speed wind tunnel for experimental verification. Laminated Object Manufacturing (LOM) facilities at the Milwaukee School of Engineering Rapid Prototyping Laboratory were used to create two mirror imaged fillets (for the top and bottom endwalls). These fillets were installed at the leading edge of the central vane on both the top and bottom endwalls as well as on the adjacent airfoils (top and bottom endwalls also) to ensure periodic flow in both passages of the test section.

<table>
<thead>
<tr>
<th>Value</th>
<th>Uncertainty Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_p</td>
<td>4.7% for C_p = -9.5</td>
</tr>
<tr>
<td>V_s</td>
<td>2.0% near wall</td>
</tr>
<tr>
<td>V_n</td>
<td>24.1% near wall</td>
</tr>
<tr>
<td>V_z</td>
<td>2.9% near wall</td>
</tr>
<tr>
<td>w_rms</td>
<td>2.8% near wall</td>
</tr>
<tr>
<td>v_rms</td>
<td>3.7% near wall</td>
</tr>
<tr>
<td>w_rms</td>
<td>1.3% near wall</td>
</tr>
</tbody>
</table>

For the remaining fillets (adjacent vanes), silicon molds of the two LOM fillets were made. The silicon molds were made by placing a fillet in a wooden box and covering half the fillet with modeling clay. Ultra-alloy silicon was poured over the exposed half of the fillet to form half the mold. After the first half of the mold cured, which required approximately 24 h, the clay was removed from the fillet. To allow air to be removed from the cavity of the silicon mold, a gating system was made by attaching straws to selected points of the fillet prior to pouring the second half of the mold. When the second half of the mold cured, the straws and fillet were removed and the mold was ready for use. A two-part polyurethane was poured into the mold cavity to form the fillets. When the polyurethane cured, the new fillet was removed from the mold and the gating system had to be broken off from the fillet. Because of the location of the adjacent vanes in the corner test section, the four extra fillets had to be cut nearly in half to fit in the correct positions. The fillets were then installed in the wind tunnel by placing a small amount of silicon adhesive between the fillet and the endwall and the fillet and the vane.

### Experimental and Computational Results

The effectiveness of the fillet was determined through flow field measurements and predictions at various flow planes along the airfoil. These planes were normal to the airfoil (with the exception of the leading edge plane) and allowed the secondary flow field velocities to be clearly seen. Throughout this section of the paper, comparisons will be made between the flow field measurements with and without the fillet (previously made for this airfoil and reported by Kang et al. [2] and Kang and Thole [3]) and the computational results for the filleted vane.

The primary interest of this study was to discern any augmentations to the vortical patterns convecting through the turbine vane passage. To this purpose the flow planes were placed orthogonal to the vane with the velocity components being measured in this plane as was illustrated in Fig. 2. The velocity vectors of these vortices, which will be referred to as the secondary flow vectors, were determined by transforming the measured local velocities \((u, v, w)\) into the mean flow direction based on that occurring at the midspan \((V_x, V_y, V_z)\). For this transforma-
tion, the inviscid turning angle was calculated based on the measured velocities at the vane midspan with the relations between the secondary velocities and the midspan velocities given in the nomenclature of this paper. The secondary flow vectors are plotted using the components normal to the inviscid mean flow direction ($V_n, V_z$). In addition to the transformed velocities, contours of the secondary kinetic energy and turbulent kinetic energy are also presented.

Prior to measuring the flowfield, a comparison of the static pressure distribution at 40 percent of the span was made between the fillet and unfilleted geometry. Figure 5 shows a comparison for the vane with and without a fillet compared with the low speed, inviscid prediction for the unfilleted vane. The results indicated no alteration to the static pressure along the airfoil in adding the fillet in the leading edge region.

**The Leading Edge Plane (Plane SP).** Figures 6(a)–(c) depicts the measured velocity vectors, normalized by $U_{inlet}$, for the filleted and unfilleted vanes and the CFD predictions for the filleted vane, respectively. As can be seen, the addition of the fillet eliminates the vortex seen in this plane. As the flow approaches the vane, it does not separate from the endwall, but rather it accelerates up the fillet. Note that the line in Fig. 6(b) indicates the location of the fillet on the filleted vane. This line indicates that the core of the horseshoe vortex lies within the space that the fillet encompasses. A small downward flow along the vane surface and top of the fillet indicates that the flow is turning down the sides of the fillet. A comparison between the measurements and predictions indicate good agreement.

Figures 7(a) and (b) present computed total pressure contours for the filleted and unfilleted (Hermanson and Thole [16]) vanes. As was described previously for no fillet, there is a gradient of total pressure approaching the vane stagnation that drives the fluid down towards the endwall. By accelerating the flow, which happens in the case of the filleted vane, the downward force of the pressure gradient is overcome by the acceleration resulting in no horseshoe vortex formation. The total pressure profile for the filleted vane indicates no curling up of the contours. The contours are climbing up the fillet indicating that the flow is accelerating.

Figures 8(a) and (b) present the measured secondary kinetic energy contours in plane SP for the filleted and unfilleted vane. These secondary kinetic energy levels are a measure of the energy level of the secondary flows. As can be seen for this plane, the levels have been reduced by an order of magnitude due to the fillet. The secondary kinetic energy level contours along the fillet are a result of the flow being turned upward. Along the vane, in both the filleted and unfilleted cases, the secondary kinetic energy levels are due to the flow splitting at the stagnation location.

The most dramatic effects of the fillet are depicted in Figs. 9(a) and (b), which present the normalized turbulent kinetic energy levels for both the filleted and unfilleted geometries. There was no
indication of a vortex within the plane for the filleted case and the resulting contours were similar to a turbulent boundary layer. The peak in turbulent kinetic energy levels decreased for the filleted vane by nearly 80 percent. The results presented in this paper clearly show that by eliminating the horseshoe vortex the turbulent kinetic energy levels at all locations in the endwall region are reduced. This is important because the turbulent kinetic energy is a large contributor to aerodynamic losses in an airfoil passage (Gregory-Smith et al. [22]). Results previously reported by Radowsky and Thole [18] have indicated that a large contributor to the high turbulent kinetic energy levels in the vortex regions are actually due to a vortex unsteadiness. The lower turbulent kinetic energy levels for the filleted vane as compared with the unfilleted vane indicate that the vortex is no longer present. Comparisons of turbulent kinetic energy between the CFD predictions and measurements did not indicate good agreement, which is to be expected given that it is believed that the vortex is highly unsteady.

Predicted streamlines for the filleted and unfilleted vanes are given in Figs. 10(a) and (b). The streamlines were released from a location that was 0–13 percent span and are colored by the normalized spanwise ($w$) component of velocity. Note that the position relative to the vane stagnation in the streamwise direction is slightly further upstream for the filleted vane ($x/c = -0.34$) as compared with the unfilleted vane ($x/c = -0.17$). It is evident that there is still a passage vortex that forms along the pressure side of the filleted vane, but the leading edge vortex does not seem to be present. Figure 10(a) also shows strong downward velocities along the suction side of the fillet. In contrasting Fig. 10(a) (the filleted vane) with Fig. 10(b) (the unfilleted vane), Fig. 10(b) clearly indicates a leading edge vortex with a stronger developing passage vortex.

**Pressure Side Planes ($PS0$ and $PS1$).** To verify the effect of the fillet on the development of the passage vortex, two downstream planes were compared. Plane $PS0$ was not measured in the unfilleted study of Kang and Thole [3] so the results of the experiment (Fig. 11(a)) will be compared to CFD results for both the filleted (Fig. 11(b)) and unfilleted (Figure 11(c)) cases. In comparing Figs. 11(a) and (b), there is good agreement between the measured and predicted secondary flows. Figure 11(c) shows that the passage vortex is definitely present in the CFD results for the unfilleted vane. The actual extent of the pressure side leg of the horseshoe vortex is hard to define in this plane because of its interaction with the cross and downflows, but is discernable by the flow turning away from the endwall. Figures 11(a) and (b), however, show that for the filleted vane there is a much different pattern. Because of the cross-passage pressure gradient, flow still travels along the endwall from the pressure side of the passage to the suction side. For the filleted vane there is no upward turning away from the endwall at this location indicating the disappearance of the pressure side leg of the horseshoe vortex at this location.

Figure 11(d) shows the normalized turbulent kinetic energy measured in plane $PS0$. The contours give no indication of a vortex and closely resemble a turbulent boundary layer. The magnitude of the peak turbulent kinetic energy has remained relatively constant from the plane $SP$ to $PS0$.

Moving farther down the pressure side of the vane to plane $PS1$, the measured secondary velocity vectors indicate a full passage vortex for the unfilleted vane (Fig. 12(b)), while the filleted vane shows the start of a passage vortex (Figs. 12(a) and (c)). The secondary velocity vectors for the filleted vane show that the vortex has not yet made a complete revolution within the measurement plane and the flow away from the endwall is relatively weak. For the unfilleted vane, the vortex does make a complete revolution and the flow away from the endwall is much stronger. The CFD results for the filleted vane shown in Fig. 12(c) indicates only a slight flow away from the endwall, as did the experiment.

The normalized turbulent kinetic energy levels for plane $PS1$ are shown in Figs. 12(d) and (e) for the filleted and unfilleted experimental results. The contours from the unfilleted experiment show a well-defined vortex core while the filleted results show much more uniform profiles in the pitch directions. The peak turbulent kinetic energy is decreased by nearly a factor of ten. In the filleted vane the largest fluctuations occur in the $v$-component of velocity, which is in contrast to the unfilleted vane where the largest fluctuations occur in the $w$-component of the velocity. Large fluctuations in the $w$-component (component normal to the endwall) indicate that for the unfilleted vane the unsteady vortex is bouncing to and from the wall.

**Suction Side Plane (Plane $SS1$ and $SS2$).** Measurements were performed along the suction side of the vane in Plane $SS1$. Figures 13(a)–(e) show the secondary velocity vectors for the experiments with and without the fillet for both measurements and
CFD predictions. Focusing on the region closest to the suction side-endwall corner, it can be seen that the secondary flows in this region for the filleted and unfilleted experiments are slightly different. The vortex in the corner region of the unfilleted vane (Fig. 13) definitely shows an upward turn whereas in the measured and computed results for the filleted vane (Figs. 13(a) and (c)) there was only a downward velocity as the flow traveled down the suction side of the fillet. Another difference between the filleted and unfilleted experimental results is the stronger crossflow associated with the passage vortex in the unfilleted case. This stronger crossflow is consistent with the observations of plane PS1 where the crossflow component of the passage vortex was smaller in the filleted case.

Figures 13(b) and (d) depict the turbulent kinetic energy for the filleted and unfilleted vanes. For the unfilleted vane the vortex structures can be seen by the regions of highest fluctuations coinciding with the vortex core of the suction side leg of the horseshoe vortex. For the filleted vane, the magnitude of the fluctuations in the suction side corner region was decreased by a factor of three. At this location, the passage vortex from the neighboring filleted vane has also progressed further downstream. Although the normal plane SS1 gives a skewed view of the neighboring vortex (since it is not normal to the neighboring vane), it can clearly be seen that even at this location, the turbulent kinetic energy levels are still lower for the filleted vane as compared to the unfilleted vane.

Further downstream at plane SS2, the computed secondary flows are presented in Figs. 14(a)–(b) for the filleted and unfilleted vanes. While a suction side vortex is present for both cases, it is much weaker for the filleted vane than for the unfilleted vane. In addition, the location of the passage vortex has shifted somewhat away from the endwall for the filleted vane. The predicted streamwise vorticity levels at this location are presented in Figs. 14(c)–(d) for both vanes. These levels indicate reduced levels in both the passage and suction corner vortices for the filleted vane as compared to the unfilleted vane.

Conclusions

Computational and experimental studies were performed on methods for reducing and/or eliminating the horseshoe vortex that forms at the leading edge of a gas turbine stator vane. A number of CFD simulations were made to design an effective fillet that resulted in a geometry that was one boundary layer thickness in height and two boundary layer thicknesses in length protruding upstream of the vane. After the effective fillet geometry was designed, flow field measurements were made to verify its performance in a test section with a large-scale, linear vane cascade.

The flowfield results for a plane parallel to the inlet flow direction and located at the leading edge verified that the vortex was no longer present. The incoming boundary layer was accelerated as it traveled up the fillet surface resulting in no leading edge vortex formation. Near the top of the fillet, the flow did turn down the fillet sides, but the secondary kinetic energy levels associated with it decreased by nearly an order of magnitude over the levels measured without the fillet. The turbulent kinetic energy levels significantly decreased indicating that the fillet reduced the unsteadiness associated with the leading edge horseshoe vortex.

The results of the flow field measurements on the pressure side of the vane, just downstream of the stagnation region, also indicated the elimination of the horseshoe vortex and a delay in the development of the passage vortex. The turbulent kinetic energy levels appeared to be more consistent with wall-generated turbulence. Farther down the pressure side of the vane, the pitch and
span flows associated with the passage vortex were detected but were reduced with the addition of the fillet. This is in contrast to the unfilleted vane where the passage vortex was fully developed, making a complete rotation much earlier in the passage. The results presented in this paper indicate that the leading edge horseshoe vortex can be eliminated. The results of this study have shown significant reductions in the turbulent kinetic energy levels and in the streamwise vorticity levels both of which are large contributors to aerodynamic losses in a turbine vane passage.

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Nomenclature

\( C \) = true chord of stator vane

\( C_p \) = static pressure coefficient, \((p - p_{\text{inlet}})/(P_{\text{inlet}} - p_{\text{inlet}})\)

\( H \) = shape factor, \( \theta / \theta_0 \)

\( k \) = turbulent kinetic energy, \( k = 1/2(u_{rms}^2 + v_{rms}^2 + w_{rms}^2) \)

\( p \) = local static pressure

\( p_{\text{inlet}} \) = inlet static pressure

\( p_{\text{total}} \) = total inlet pressure

\( \Delta p \) = normalized total pressure, \( 1 - ((P_{o,ms} - P_o)/(P_{o,ms} - p_{\text{inlet}})) \)

\( \text{Re}_{in} \) = Reynolds no. defined as \( \text{Re}_{in} = C U_{inlet} / \nu \)

\( s \) = surface distance along vane measured from stagnation

\( S \) = span of vane

\( \text{SKE} \) = secondary kinetic energy,

\( (V_u^2 + V_z^2)/(1/5) \cdot U_{inlet}^2 d z \)

\( u_t \) = shear velocity, \( \sqrt{\tau_{xx}/\rho} \)

\( u, v, w \) = velocity in inner coordinates, \( u, \nu, \nu \)

\( U, V, W \) = mean velocity in X, Y, Z directions

\( U_{inlet} \) = incident upstream velocity

\( V_u \) = streamwise velocity component,

\( u \cos \theta_{ms} + v \sin \phi_{ms} \)

\( V_u \) = secondary velocity in pitch direction, \(- u \sin \phi_{ms} + v \cos \phi_{ms} \)

\( V_z \) = secondary velocity normal direction

\( x, y, z \) = local coordinates defined at measurement location

\( X, Y, Z \) = global coordinates defined from stagnation location

\( \delta_{99} \) = boundary layer thickness

Fig. 13 Secondary velocity vectors in plane SS1 for measurements of the (a) filleted vane and computations of the (c) filleted vane and measurements of the (d) unfilleted vane. Contours of turbulent kinetic energy are shown for the (b) filleted and (e) unfilleted vanes.

Fig. 14 Comparison of computed secondary flows (a,b) and vorticity (c,d) in plane SS2 for the filleted (a,c) and unfilleted (b,d) vane.
\( \delta \) = displacement thickness
\( \theta \) = momentum thickness
\( \rho \) = density
\( \Omega \) = streamwise vorticity, \( \Omega_x \cos(\Psi_{ms}) + \Omega_y \sin(\Psi_{ms}) \)
\( \Omega_x, \Omega_y \) = x and y vorticity components
\( \tau_w \) = wall shear stress
\( \nu \) = viscosity
\( \Psi_{ms} \) = inviscid mid-span turning angle, \( \tan^{-1}(v_{ms}/u_{ms}) \)

Subscripts
- \( \text{in} \) = inlet
- \( \text{ms} \) = midspan values
- \( \text{rms} \) = root mean square

Superscripts
+ = normalization using inner scaling coordinates

References