Numerical Investigation of Turbulent Junction Flows

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Turbulent junction flows are known to exhibit a bimodal behavior of the horseshoe vortex that can be described by a random switching between a zero-flow and a backflow mode. The physical mechanism that causes the bimodal behavior is not well understood. Large-eddy simulations of a canonical junction flow geometry, the Rood wing, were carried out for a Reynolds number based on approach flow velocity and maximum thickness of 7000, and the junction flow physics were analyzed. The approach boundary-layer profile, mean flow data, and turbulent statistics obtained from the simulation are in good agreement with measurements at Penn State University. The present results for $Re = 7000$ clearly exhibit a bimodal behavior that is characterized by a forward and backward motion and intermittent loss of coherence of the horseshoe vortex. Instantaneous flow visualizations reveal that the interaction of pockets of elevated upstream boundary-layer turbulence with the horseshoe vortex can both strengthen and weaken the horseshoe vortex. This suggests that the bimodal behavior may be triggered by the turbulent boundary layer. In addition, simulations with two different circular endwall fillets were carried out. In accordance with the literature, the fillets were found to suppress the bimodal behavior.

I. Introduction

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HEN a turbulent boundary layer (BL) interacts with a body, such as a turbine blade, a horseshoe vortex (HV) forms around the leading edge of the body. Such turbulent junction flows can exhibit a bimodal behavior that is characterized by the more or less random alternation between a zero-flow and a backflow state [1]. The zero-flow state or mode is characterized by a weak HV closer to the junction and is present for about 20–30% of the mode switching period. The backflow mode features a strong HV with strong reverse flow and is prevalent for 70–80% of the mode switching period. Turbulent junction flows occur in many technical applications, such as in heat exchanger tube banks, pin fin arrays in heat sinks, bridge piers, submarine conning towers, or low-pressure-turbine (LPT) flows. For example, measurements by Marks and coworkers [2–4] and implicit large-eddy simulations (ILESs) by Gross et al. [5] indicate that the bimodal behavior of the HV for a linear LPT cascade may be responsible for an intermittent loss of coherence of the passage vortex. Smoke line visualizations by Wang et al. [6] for a linear turbine cascade at a Reynolds number of 10,000 also exhibit a bimodal behavior of the HV with a frequency based on axial chord length $c$ and inlet (freestream) velocity $u_\infty$ of $\approx 0.6$. Because the passage vortex is one of the dominant loss sources in LPT flows [7], the development of a solid understanding of the physical mechanism

Nomenclature

$\Delta$ = grid length scale
$\delta$ = boundary-layer thickness, Kronecker symbol
$\delta^*$ = displacement thickness
$\theta$ = momentum thickness
$\mu$ = dynamic viscosity
$\rho$ = density
$\tau$ = stress tensor
$\omega$ = vorticity

Subscripts

$T$ = turbulent
$w$ = at the wall
$0$ = inflow, stagnation conditions
$\infty$ = freestream conditions

Superscript

$+$ = in wall units
responsible for the bimodal behavior is desirable. The development of such understanding could also inform the design of technologies aimed at a reduction of the associated high heat transfer rates that can be a concern for turbomachinery applications.

Devenport and Simpson [1] investigated the bimodal behavior for a Rood wing junction flow at a chord Reynolds number of $1.15 \times 10^6$. The Rood wing airfoil, which is named after E. P. Rood, consists of a 3:2 ellipse that is joined with a NACA 0020 airfoil at the maximum thickness. The frequency of the mode switching based on BL thickness $\delta$ and $u_\infty$ in the Devenport and Simpson [1] experiment was $f_0/\delta u_\infty \approx 0.05$. The mode switching was found to be aperiodic, which might be expected for a turbulent flow. Devenport and Simpson [1] remarked that the mode switching can lead to increased turbulence velocity fluctuations and heat transfer rates (up to 300% for high-pressure turbines) as well as strong pressure fluctuations. All of these effects are usually undesirable, which provides additional motivation for research aimed at an improved understanding of the physics of turbulent junction flows. An improved understanding of the flow physics and in particular the origin of the unsteadiness will potentially lead to ideas on how to control or suppress the bimodal behavior. Devenport and Simpson [1] also suggested that the bimodal behavior may be related to turbulent BL bursting events. Finally, the bimodal behavior was determined to be more dependent on the nose bluntness, which sets the adverse pressure gradient, than the Reynolds number, as also shown by Mehta [8] and Olesen and Simpson [9].

Simpson [10] provided a review paper on turbulent junction flows. Although turbulent junction flows are fairly common, the associated physics are still not fully understood. Experiments by Agui and Andreopoulos [11] indicated that large-scale turbulent BL structures may be responsible for an aperiodic displacement of the HV in the streamwise direction that is followed by an eruption of near-wall fluid and the formation of a smaller counter-rotating secondary vortex (SV). Praisner and Smith [12] took measurements near a symmetric airfoil with cylindrical leading edge and 5:1 trailing edge fairing. They found a reoccurring sudden strengthening of the HV that was linked to a HV displacement toward the leading edge (backflow state) and a concomitant strengthening of the SV. As the HV gets closer to the leading edge, through induction it causes the SV to move rapidly away from the endwall, thus leading to the zero-flow state. These events have a periodicity of approximately 150$^+$ in wall units which is close to the period of the bursting events of the undisturbed impinging turbulent BL, which suggests that the BL events may be related to the bimodal behavior. Burst in turbulent BLs refer to the quasi-periodic ejection of near-wall fluid. Particle image velocimetry (PIV) measurements of a flat plate turbulent BL by Adrian et al. [13] suggest that the bursting events are related to hairpin packets. Turbulent junction flow experiments for a tapered cylinder by Sabatino and Smith [14] revealed a correlation between the HV mode switching period and the turbulent BL statistics. In the symmetry plane, the dominant period of the HV motion was 260$^+$ and the period of the surface temperature fluctuations was 200$^+$. Sabatino and Smith [14] also proposed that the ingestion of hairpin vorticity by the HV strengthened the HV and led to a HV movement toward the junction and the ejection of an SV.

Direct numerical simulations (DNSs), large-eddy simulations (LESs), and hybrid simulations (combination of Reynolds-averaged Navier-Stokes [RANS] and LES) constitute another means to investigate the physics of turbulent junction flows. Detached eddy simulations (DESs) by Park et al. [15] for the Rood wing geometry at $Re = 115,000$ clearly revealed the backflow state with coherent HV and times where three-dimensional (3-D) BL hairpin vorticity is “wrapped around” the HV and “amplified.” The amplification was attributed to a centrifugal Görtler-like instability. It was argued that the ingestion and amplification of 3-D vorticity by the HV leads to a loss of coherence of the HV and the establishment of the zero-flow state. Eventually a new weaker coherent HV forms upstream of the junction. The simulations were in reasonable agreement with the experiments by Devenport and Simpson [1]. Allen and Naitoh [16] conducted a fundamental investigation of the HV stability and found that the velocity profile between the endwall and the point of maximum reverse flow velocity satisfies the Rayleigh criterion and that centrifugal instability occurs for Görtler numbers larger than one. Wind tunnel experiments and LES by Gand [17] for a wing junction geometry at $Re = 2.8 \times 10^6$ displayed a bimodal behavior with a frequency of $0.05 < f_0/\delta u_\infty < 0.1$. Escauriza and Sotiropoulos [18] performed DES of the flow past a wall-mounted circular cylinder. Instantaneous flow visualizations revealed eruptions of near-wall vorticity whose intensity and frequency increased with Reynolds number. These eruptions were related to hairpin vortices that “rolled up” around the HV and led to a loss of coherence of the HV. Schwämmle et al. [19] performed a DNS of the turbulent flow through a first-stage high-pressure stator cascade at $Re = 10,000$. The simulation revealed a pronounced aperiodic motion of the HV. Similarly, Cui et al. [20] carried out an LES of the flow through a T106a LPT cascade and identified an unsteadiness of the HV.

Smith and Walker [21] conducted a detailed analysis of passive and active control strategies for turbulent junction flows. For turbomachinery applications, it is desirable to weaken the HV as the energy bound in the HV and the resulting passage vortex is lost. The addition of an endwall fillet weakens the HV by reducing the adverse pressure gradient ahead of the suction (e.g., [22]). Various large fillets at the leading edge of the airfoil–endwall junction have shown promise in both cascade and engine-representative environments. Leading-edge features are designed to prevent the development of the HV by accelerating the incoming BL. Zess and Thole [23] demonstrated the elimination of the HV and an order of magnitude reduction in local turbulent kinetic energy for a fillet upstream of a vane, and Becq et al. [24] measured a 7% reduction in cascade aerodynamic loss for a blade with a fillet. A bulb on the blade leading edge reduced losses by 47% in a study by Sauer et al. [25]. The HV can also be effectively eliminated with suction (e.g., [26, 27]). Other forms of passive flow control were also employed to reduce the junction flow unsteadiness. For example, Olesen and Simpson [28] used fences and Apsilidis et al. [29] investigated the effect of wall roughness.

To conclude, some of the earlier research provided evidence that turbulent BL events can trigger the bimodal behavior. Other prior research suggests that the dominant frequency associated with the bimodal behavior scales with the BL edge velocity and leading-edge diameter. The lack of a conclusive explanation of the bimodal behavior provided the motivation for the present turbulent junction flow simulations and experiments for the Rood wing geometry. First, the setup of the experiments and simulations is discussed. Then, the mean flow and turbulent statistics obtained from both approaches are compared for a Reynolds number of 7000. In the following section, based on snapshots of the flowfield, the dynamics of the HV are investigated. Next, the effect of circular endwall fillets on the unsteady junction flow is explored. Finally, a brief summary and conclusions are offered.

II. Methodology

A. Wind Tunnel Experiments

The Rood wing junction flow experiments were carried out in the closed-loop wind tunnel at Penn State University [30–34] (Fig. 1). This tunnel is fully optically accessible and has a test section width and height of 1.12 and 0.55 m, respectively. The Rood wing was made from polished clear acrylic and has a chord length, maximum thickness, and span of $c = 40$ cm, $t = 9.42$ cm, and $H = 54.5$ cm, respectively. Because of the low Reynolds number, small freestream turbulence, and smooth surface finish, the BL on the Rood wing remained mostly laminar. Pressure taps were embedded at 50% span. A three-component laser Doppler velocimetry (LDV) system, a stereo PIV system, and an infrared camera were employed for flow diagnostics. An uncertainty analysis of the LDV measurements using the approach of Moffat [35] indicated an uncertainty of approximately 5% in the time mean velocities. A PIV system resolution of 0.04 pixels/mm was achieved with 200 mm lenses attached to two high-speed cameras that both had a standoff distance of approximately 1 m from the field of view. The particle images were processed using La Vision’s Davis software, with nominally 32 x 32 pixel windows with 75% overlap. A total of 8740 samples (image pairs)
were obtained at a sample rate of 2 kHz. A prior study indicated that this number was sufficient to achieve statistical convergence of the mean and root mean square (RMS) quantities. An uncertainty analysis for the PIV measurements using the correlation statistics approach of Wieneke [36] indicated an estimated time mean uncertainty ranging from less than 1% near the freestream to approximately 11% in the center of the HV core. For the experiments, time convergence of the statistics was determined by examining the mean and root-mean-square of the velocity components (as well as the turbulence kinetic energy) for samples of sizes 4000, 6000, and 8000. The results generally varied by less than 2% for several important locations (freestream, near the HV time-mean core, close to the wing leading edge) for sample sizes greater than 6000, although all 8740 samples were used in the time-mean results shown in this paper. Using a heating element that was custom made from Inconel wire, a constant heat flux from the endwall into the endwall BL was maintained. By measuring the endwall temperature with the infrared camera, the wall heating could be estimated. The surface temperature resolution for the endwall heat transfer coefficient measurements was approximately 2 mm/pixel with the infrared camera, at a standoff distance of 55 cm and a sensor resolution of 640 × 480 pixels. The approach of Moffat [35] was used to estimate uncertainties of the heat transfer coefficient measurements, which were found to be approximately 14% at Re = 7000. The inflow BL had a long development length (2.58 m) on a flat plate, after a trip located at the top of a rounded leading edge. Prior three-component LDV measurements in the tunnel have indicated that this approach generates a two-dimensional (2-D) BL and a uniform freestream at the axial location where the wing is located. Furthermore, the symmetry of the heat transfer measurements indicated that the flow was nominally 2-D.

The tunnel has been used to study junction flows for a range of Reynolds numbers (7000–80,000) and freestream turbulence levels (1–20%) [31–34] (with turbulence grid). The integral length scale of the tunnel turbulence level was relatively large, as indicated in Ref. [32], likely as a result of a resonance of the tunnel test section on a timescale much larger than the dynamic events considered here. Note that Ref. [34] shows that good agreement was achieved to Davenport and Simpson’s [1] junction flow study at a similar Reynolds number, despite their lower freestream turbulence level of 0.2%. The freestream temperature was 286 K. The freestream turbulence intensity was roughly 1%. A stereo arrangement of two cameras on opposite sides of the test section was used to image the junction flow region using high-speed PIV. The laser sheet for the particle illumination is routed out of the nose of the airfoil along the airfoil symmetry plane, through a removable transparent nose-piece. This is done to reduce laser glare on the endwall, which allows for measurements very close to the endwall. This technique also maximizes the amount of particle-reflected light reaching the cameras. Incoming BL mean and fluctuating velocities 1.2 chords upstream of the airfoil were characterized with a two-component LDV system. Both the PIV and LDV systems used one micron atomized particles of castor oil as the flow tracers. These tracer particles have an effective Stokes number much less than one to follow the fluctuations in the flow. A detailed diagram of the experimental setup is provided in Fig. 1. More details about the experiment as well as junction flow measurements can be found in Ref. [34].

B. Simulations

1. Numerical Method

Accompanying LESs were carried out with a research computational fluid dynamics code by Gross and Fasel [37]. The code solves the compressible Navier–Stokes equations in curvilinear coordinates. For robustness, especially on highly distorted grids, a finite-volume formulation is employed. The convective terms of the Navier–Stokes equations are discretized with a high-order-accurate scheme. Details regarding the higher-order-accurate discretization of the convective terms are provided in Ref. [38]. The discretization of the viscous terms is fourth-order accurate. The implicit second-order-accurate trapezoid rule is employed for time integration.

2. Turbulence Modeling

The subgrid stress (SGS) tensor,

\[ \tau_{ij} = \bar{\rho} \left( u_i \tilde{u}_j - \bar{u}_i \bar{u}_j \right) \]  

(1)
is modeled as

$$\tau_{ij} = -2\mu_f \left( S_{ij} - \frac{1}{3} S_{kk} \delta_{ij} \right) + \frac{1}{3} \tau_{kk} \delta_{ij}$$  \hspace{1cm} (2)$$

where

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$  \hspace{1cm} (3)$$

is the strain rate tensor of the resolved scales. Here, the overbar indicates time averages and the tilde indicates mass averages. The deviatoric part of $\tau_{ij}$ is proportional to an SGS (unresolved) eddy viscosity $\mu_f$. Because of the good resolution of the present simulations, the eddy viscosity is of the same order of magnitude as the molecular viscosity such that the model contribution is overall small. According to Erlebacher et al. [39] the isotropic part $\tau_{kk}$ is very small compared with the thermodynamic pressure and hence neglected. The heat flux is computed as

$$q_i = -c_p \left( \frac{\mu}{Pr} + \mu_f \frac{Pr}{Pr_f} \right) \frac{\partial \tilde{T}}{\partial x_i}$$  \hspace{1cm} (4)$$

For the wall-adapting local eddy-viscosity (WALE) model by Nicoud and Ducros [40], the unresolved eddy-viscosity is modeled as

$$\mu_f = \bar{\rho} \Delta^2 C_w \frac{(S_{ij} S_{ij})^{3/2}}{(S_{ii} S_{jj})^{3/2} + (S_{ij} S_{ij})^{3/4}}$$  \hspace{1cm} (5)$$

with

$$S_{ij} = \frac{1}{2} (g_{ij}^2 + g_{ji}^2) - \frac{1}{3} g_{kk} \delta_{ij}$$  \hspace{1cm} (6)$$

$$g_{ij}^2 = \delta_{jk} \delta_{ij}$$  \hspace{1cm} (7)$$

$$g_{ij} = \frac{\partial g_i}{\partial x_j}$$  \hspace{1cm} (8)$$

and model constant $C_w = 0.5$. For the present results, the grid length scale $\Delta$ was chosen as the geometric average of the cell dimensions. The WALE model accounts for the effects of both the strain and rotation rate of the smallest resolved turbulent fluctuations, and it recovers the proper $y^+$ near-wall scaling for the eddy viscosity.

3. Nondimensionalization

The maximum Rood airfoil thickness $t$ was chosen as reference length scale. With this scaling, the chord length becomes $c/t = 4.239$. The freestream velocity $u_\infty$ was taken as reference velocity. Time was made dimensionless with $t/u_\infty$.

4. Simulation Setup

For the present simulations, because of the high computational cost associated with resolving turbulent velocity fluctuations in the freestream, the freestream turbulence was set to zero. The Reynolds number based on maximum thickness was $Re = 7000$ (lowest Reynolds number of the experiments [30,31,33,34]). The reference Mach number was set to $M = 0.1$. This Mach number is small enough to reasonably approximate the incompressible flow assumption without negatively affecting the convergence characteristics of the implicit time-integration scheme. The laminar and turbulent Prandtl numbers were $Pr = 0.72$ and $Pr_f = 0.9$.

5. Computational Grids

Two 3-D computational grids (baseline and fine) were employed for the present simulations. Compared with the baseline grid, the fine grid has 50% more cells in all three directions. Both 3-D grids were based on 2-D grids (Fig. 2) that were generated with a Poisson grid generator [41]. Grid line stretching was employed near the outflow to dissipate wake structures. The width of the wind tunnel test section, made dimensionless with the profile thickness, is 11.89. The transverse domain boundaries of the grid are at $\pm 4.239$ (block 1) and $\pm 2.120$ (blocks 2 and 3). The total width of block 1 (8.478) is thus slightly lower than the width of the wind tunnel test section. Block 3 was employed for temporal turbulent BL simulations. Here, temporal refers to a flow that develops in time but not in the streamwise direction. Block 2 was made long enough to allow the turbulent BL to reach equilibrium before interacting with the Rood wing. The leading edge of the Rood wing was located at $x = y = 0$ with $x$, $y$, and $z$ pointing in the streamwise, transverse (crossflow), and spanwise direction, respectively. The locations of the inflow and outflow boundaries are provided in Table 1.

Only half of the span, $H/(2t) = 2.914$, was simulated and symmetry conditions were enforced at midspan. Toward that end, the 2-D grids were extruded in the spanwise direction over a spanwise distance of 2.914 (Fig. 3). A grid line distribution that provides grid line clustering near the lower wall and blends toward an equidistant spacing near the wall,

$$z_0 = 0$$  \hspace{1cm} (9)$$

$$z_1 = \Delta z$$  \hspace{1cm} (10)$$

$$z_k = z_{k-1} + \left[ 0.1 \left( \frac{k - K}{2 - K} \right)^{c} + 1 \right] (z_{k-1} - z_{k-2}) \quad \text{for } k \geq 2$$  \hspace{1cm} (11)$$

was employed. Here, $K$ is the number of cells in the spanwise direction. The wall-normal grid line spacing at the endwall is

<table>
<thead>
<tr>
<th>Block</th>
<th>Inflow</th>
<th>Outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>-4.239</td>
<td>8.478</td>
</tr>
<tr>
<td>Fine</td>
<td>-19.067</td>
<td>-4.239</td>
</tr>
<tr>
<td></td>
<td>-23.304</td>
<td>-19.067</td>
</tr>
<tr>
<td></td>
<td>-24.661</td>
<td>-19.942</td>
</tr>
</tbody>
</table>

Fig. 3 Outline of baseline computational domain.

![Fig. 3 Outline of baseline computational domain.](image-url)
The near-wall grid resolution in wall units for the approach BL is provided in Fig. 5. The near-wall grid line spacings in wall units for the baseline grid upstream of the junction, for \( x > -18 \), are \( \Delta x^+ = 20 \), \( \Delta y^+ = 8.8 \), and \( \Delta z^+ = 0.32 \) and close to those chosen by Nicoud and Ducros [40] for their LES test problem (28, 8.8, and 2.1, respectively). For their LES, Nicoud and Ducros employed sixth-order-accurate finite differences for the convective terms and a fourth-order-accurate discretization for the viscous terms. The following approach was taken to prevent the turbulent inflow data for block 2. For the temporal simulations, periodicity conditions were enforced in the transverse direction. The portion of the block 1 inflow boundary that extends past the width of block 2 received inflow data from the matching opposite end of the block 2 outflow boundary. For blocks 2 and 3, periodicity conditions were enforced in the transverse direction. A nonreflecting boundary condition [43] was applied at the transverse domain boundaries and outflow boundary of block 1.

### Table 2: Number of cells

<table>
<thead>
<tr>
<th>Block</th>
<th>Baseline grid</th>
<th>Fine grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>410 × 200 × 96</td>
<td>615 × 277 × 133</td>
</tr>
<tr>
<td>2</td>
<td>245 × 150 × 96</td>
<td>357 × 225 × 133</td>
</tr>
<tr>
<td>3</td>
<td>70 × 150 × 96</td>
<td>108 × 225 × 133</td>
</tr>
<tr>
<td>Total</td>
<td>12,408,000</td>
<td>36,572,340</td>
</tr>
</tbody>
</table>

\[ \Delta z = 4 \times 10^{-4} \] for both grids, and the constant \( c \) is 1.06 for the baseline grid and 1.04 for the fine grid. The number of cells per block and the total number of cells are provided in Table 2. In addition to the baseline and fine grids with straight endwall junction, two grids with circular endwall fillet were generated by modifying the baseline block 1 grid near the endwall (Fig. 4). The fillet radius was \( r/t = 0.1 \) for fillet 1 ("F1") and 0.2 for fillet 2 ("F2"). The number of cells per block is identical to those for the baseline grid (Table 2).

Because of limited computational resources, turbulent statistics were only computed for the baseline grid. Contours of the ratio of the grid length scale, \( \Delta \), to the Kolmogorov length scale, \( L_K = (Re \times \nu)^{-0.25} \), with turbulent dissipation rate \( \epsilon \), are provided in Fig. 8 for the baseline grid. This ratio is less than four for the interaction region and lower than 10 for the approach BL. According to Moin and Mahesh [42], the grid resolution for DNSs must be sufficient to allow for scales of the same order of magnitude as the Kolmogorov length scale to be resolved. For the blue-shaded regions in Fig. 8 the grid resolution is of the order of the Kolmogorov length scale. For the red-shaded regions (block 1 inflow corners and outflow) the grid resolution is of the order of the Kolmogorov length scale. This implies that the grid resolution for the approach BL and junction region are sufficient for LES. The good agreement of the present results with the experimental data provides additional supporting evidence that the baseline grid resolution is sufficient for accurately resolving the unsteady fluid dynamics.

### 6. Boundary Conditions

All walls were considered as isothermal. Slip wall conditions were employed at the spanwise domain boundary (half-span of Rood wing). The time-dependent outflow data from the temporal simulation (block 3) were fed into block 2 at the inflow boundary. The turbulent BL was allowed to reach equilibrium in block 2 before it was fed into block 1. Because the block 2 outflow is periodic in the spanwise direction, the portion of the block 1 inflow boundary that extends past the width of block 2 received inflow data from the matching opposite end of the block 2 outflow boundary. For blocks 2 and 3, periodicity conditions were enforced in the transverse direction. A nonreflecting boundary condition [43] was applied at the transverse domain boundaries and outflow boundary of block 1.

### 7. Temporal Boundary-Layer Simulation

Block 3 was employed for temporal BL simulations that provided the turbulent inflow data for block 2. For the temporal simulations, periodic boundary conditions were employed in the streamwise direction. The following approach was taken to prevent the BL from growing: After each timestep, the primitive variables, \( \mathbf{q} = [u, v, w, p, T] \), were averaged in the streamwise and transverse direction,

\[
\bar{\mathbf{q}}(z) = \frac{\int \int q(x, y, z) dx dy}{L_b}
\]

where \( L \) and \( b \) are the streamwise and transverse extent of the computational domain. The average was then subtracted from the instantaneous data to obtain the fluctuations. Finally, a turbulent profile from a RANS simulation with k-\( \omega \) turbulence model was added.

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**Fig. 4** Computational grid in symmetry plane \((y = 0)\) for a) fillet 1 \((r = 0.1)\) and b) fillet 2 \((r = 0.2)\).
With this approach a temporal turbulent BL could be maintained. In the freestream, the conservative variables, $Q = [\rho, \rho u, \rho v, \rho w, \rho e]^T$, were forced to the RANS profile via

$$\frac{\partial Q}{\partial t} = (Q - Q_{RANS}) \times f$$

(14)

Fig. 6 Radial, circumferential, and spanwise near-wall grid resolution in wall units for a) baseline grid and b) fine grid.

The blending function $f$ was set to zero for $z \leq 0.75$, one for $z \geq 1.5$, and linearly varied in between. The shifted periodic boundary condition approach by Munters et al. [44] was employed to prevent the spanwise locking of large-scale structures. The block 3 inflow and outflow plane data were shifted with respect to each other in the spanwise direction by 0.339 (i.e., a shift of 12 cells for the baseline grid and 19 cells for the fine grid).

8. Startup of Simulations

Two-dimensional simulations were carried out as a precursor to the 3-D simulations. Instantaneous flowfields from the 2-D simulations were extended in the spanwise direction to obtain initial conditions for the 3-D simulations. In addition, before commencing the 3-D simulations, the temporal BL simulations were initialized and advanced in time until the near-wall turbulence was fully developed. The computational timestep was $\Delta t = 0.005$ (baseline grid) and 0.0035 (fine grid) for the original Rood wing case and 0.001 for the cases with fillet. Choi and Moin [45] showed that $\Delta t \leq 0.4$ is sufficient for LES. For the largest timestep of the present simulations $\Delta t \approx 0.09$. The time intervals for the startup (initialization to beginning of time averaging) and for the computation of the time averages and the turbulent statistics are provided in Table 3.

<table>
<thead>
<tr>
<th>Case</th>
<th>Startup</th>
<th>Time averaging</th>
<th>Turbulent statistics ($t_{u*}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight (baseline grid)</td>
<td>45</td>
<td>125</td>
<td>175</td>
</tr>
<tr>
<td>Straight (fine grid)</td>
<td>12</td>
<td>26.7</td>
<td>—</td>
</tr>
<tr>
<td>Fillet 1</td>
<td>21.4</td>
<td>23</td>
<td>—</td>
</tr>
<tr>
<td>Fillet 2</td>
<td>16</td>
<td>34</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 7 Number of cells within boundary layer ($z \leq \delta_{99}$) and viscous sublayer ($z^+ \leq 10$).

$$\bar{q}(x, y, z) = q(x, y, z) - \bar{q}(z) + \bar{q}_{RANS}(z)$$

(13)

The blending function $f$ was set to zero for $z \leq 0.75$, one for $z \geq 1.5$, and linearly varied in between. The shifted periodic boundary condition approach by Munters et al. [44] was employed to prevent the spanwise locking of large-scale structures. The block 3 inflow and outflow plane data were shifted with respect to each other in the spanwise direction by 0.339 (i.e., a shift of 12 cells for the baseline grid and 19 cells for the fine grid).

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Fig. 8 Ratio of grid length scale to Kolmogorov length scale ($0 < \Delta/L_K < 20$) for a) $z = 0.26$ and b) $x = -0.17$ plane (baseline grid).
III. Analysis

A. Turbulent Approach Flow Boundary Layer

Instantaneous flow visualizations of the junction region obtained with the \( Q \)-criterion by Hunt et al. [46] and the \( \lambda_2 \)-criterion by Jeong and Hussain [47] are shown in Fig. 9 for the baseline grid. Because the two visualizations are very similar in particular with respect to the HV core size in what follows, exclusive use will be made of the \( Q \)-criterion. Instantaneous isosurfaces of the \( Q \)-criterion colored by the streamwise velocity \((0 < u < 1)\) for the entire computational domain are shown in Fig. 10. The visualizations reveal that the data from the temporal BL simulation (block 3) are fed seamlessly into block 2 (inflow boundary of spatial simulations). Near-wall streaks and hairpin vortices can be observed inside the turbulent approach BL. The Rood wing appears embedded in the turbulent BL. Away from the junction, attached laminar BLs originate from the Rood wing leading edge and then separate at the maximum thickness location. A Kelvin–Helmholtz instability of the separated BLs leads to the shedding of spanwise coherent structures and turbulent breakdown. Few structures are observed near the transverse and outflow boundaries of block 1 where the grid resolution is poor. The instantaneous flowfields for the baseline and fine grid appear to be in good qualitative agreement. As would be expected for an LES, smaller-scale motion is resolved on the fine grid.

LDV measurements one chord length upstream of the Rood wing provided displacement- and momentum-thickness-based Reynolds numbers of \( Re_\delta = 639 \) and \( Re_\vartheta = 448 \). The corresponding shape factor is \( H = Re_\vartheta / Re_\delta = 1.43 \). These values had to be matched in the simulations to allow for a direct comparison with the PSU measurements [30,31,33,34]. The \( \delta_{99} \) BL thickness is sensitive to the quality of the time average. Therefore, for the integration of the displacement and momentum thickness, the BL edge was taken as the wall-normal location where the crossflow vorticity dropped below 0.01% of the wall vorticity. The cutoff value was determined by numerical experimentation. Because the BL edge location only provides the bound for the integration, the displacement and momentum thickness are relatively insensitive to its precise value. Because the initial BL development inside block 2 was different for the two

![Fig. 9 Instantaneous isosurfaces of \( Q = 10 \) (left) and \( \lambda_2 = -10 \) (right).](image)

![Fig. 10 Instantaneous isosurfaces of \( Q = 0.5 \) colored by streamwise velocity for a) baseline grid and b) fine grid.](image)
cases, to match the experimental reference data one chord length upstream of the leading edge, the block 2 length was adjusted (see Table 1). The displacement and momentum thickness Reynolds number as well as the shape factor obtained from block 2 of the simulations are provided in Fig. 11a. The symbols represent the measured BL properties one chord-length upstream of the Rood wing. The displacement and momentum thickness are growing in the streamwise direction and the shape factor is approaching a value of $H \approx 1.5$. This shape factor is slightly outside the accepted range of $H = 1.3 - 1.4$ for turbulent BLs, which can be attributed to the low Reynolds number [48]. For both simulations the displacement thickness, momentum thickness, and shape factor are within roughly 6, 1, and 6% of the experimental values, which was considered acceptable. In Fig. 11b the skin-friction coefficient obtained from the simulations are compared with the van Driest relationship [49]. As the turbulent BL reaches equilibrium for $Re_{\theta} > 400$, it tracks the reference with adequate accuracy. The computed and measured (LDV) velocity profiles one chord length upstream of the junction are in good agreement (Fig. 13a). The agreement of the velocity distributions obtained from both simulation and PIV measurements are compared upstream of the leading edge, are shown in Fig. 15a. The profile shape and maximum reverse flow velocity obtained from the simulations are in adequate agreement with the experiment. Figure 15b provides spanwise velocity profiles for the center of the downwash region at $z = 0.15$. Compared with the experiment, the maximum mean downwash velocity is slightly underpredicted for the baseline grid. Profiles of the turbulent kinetic energy and the Reynolds shear stress near the HV core of the time-averaged flow is situated at $x = -0.028$. Two limiting skin-friction lines originate from the saddle point and extend in the crossflow direction. These limiting skin-friction lines constitute the mean BL separation line. The node is situated where the dividing streamline between the HV and the smaller reverse flow vortex meets the wall (Fig. 17). The mean-flow skin friction is close to zero in the vicinity of both singular points and quite large in the shoulder regions (Fig. 18a). By maintaining a constant wall temperature, the effect of the unsteady flow on the wall heat transfer could be measured with an infrared camera in the experiments. The heat transfer coefficient is $h = q/\Delta T$, where $\Delta T = T_w - T_{\infty}$ is the difference between the wall.
and freestream temperature and \( q = -k \partial T/\partial z \) is the heat flux with thermal conductivity \( k = \mu c_p/Pr \) and wall distance \( z \). The Stanton number, which is defined as \( St = h/(\rho \omega_u c_p) \), can be computed from the dimensionless variables via

\[
St = \frac{-\mu (\partial T/\partial z)_w}{RePr(1 - T_w)}
\]

(15)

The Stanton number peaks in the stagnation point region (Fig. 18b). The region of large heat transfer follows the leading-edge curvature, which suggests that it is directly related to the HV. The computed Stanton number for the junction region (Fig. 18b) is several times larger than in the experiment (Fig. 19). This discrepancy, which is not well understood at this time, may be a result of the heat capacity of the wall in the experiment. Because of the good agreement of the baseline and fine grid mean flow results with each other and
Fig. 15  Velocity profiles in interaction region: a) $x = -0.1$ and b) $z = 0.15$.

Fig. 16  Profiles of a) turbulent kinetic energy and b) $\overline{u'w'}$ Reynolds stress in interaction region ($x = -0.16$) (baseline grid).

Fig. 17  Streamlines in symmetry plane (LES). Solid lines: baseline grid; dashed lines: fine grid.

Fig. 18  Time averaged a) surface streamlines and skin-friction coefficient contours and b) Stanton-number contours for baseline grid LES.

Fig. 19  Measured Stanton number.
with the PIV data and because of the lower computational expense of the baseline grid simulations (especially when considering that many periods of the low-frequency bimodal behavior had to be captured), it was decided to exclusively employ the baseline grid for all of the following results.

C. Instantaneous Flow

Instantaneous isocontours of the skin-friction coefficient and Stanton number are provided in Fig. 20. The visualizations reveal unsteady flow structures in the approach flow and several organized structures that wrap around the leading edge of the Rood wing. Both visualizations hint at an antisymmetric instantaneous HV. An instantaneous visualization of the unsteady flow exhibits multiple hairpin structures upstream of the junction (Fig. 21).

In Fig. 22 the kinetic energy of the velocity fluctuations, \( k \), is plotted versus time for four different locations in the symmetry plane. For a location far upstream of the interaction (x = -4) the kinetic energy contained in the fluctuations is less than 0.1. Under the isotropic turbulence assumption, the magnitude of the fluctuations is \( \sqrt{2/3k} \) and thus 25% of the free-stream velocity. Location x = -0.6 is close to the saddle point, and locations x = -0.4 and x = -0.2 are in the reverse flow region. The data for x = -0.6 and x = -0.4 are correlated. For example, both time series show peaks near t ≈ 90. The data for x = -0.2 display the largest spikes and appears correlated with the other time series.

Spectra of the kinetic energy of the velocity fluctuations were computed over an interval of 170 and are provided in Fig. 23. The spectra were obtained directly from Fourier transforms and also estimated with the maximum entropy method (MEM) by Ghil et al. [50] using \( M = 1500 \). The MEM is well suited for analyzing short time series that contain only a limited number of periods of a dominant mode. The spectrum for the upstream BL (x = -4) has no pronounced peaks. The spectrum for the junction region (x = -0.2) has a pronounced low-frequency peak at \( f \approx 0.15 \) and overall higher amplitudes. The prior research [17] suggests that this low-frequency peak is associated with the bimodal behavior of the HV.
For the times when the $x = -0.2$ data show peaks, the HV is relatively coherent and far forward of the junction (Fig. 24). At times when the $x = -0.2$ fluctuations are low, the HV is located closer to the Rood wing (Fig. 25). In between, time instances can be identified when the HV coherence is very low, which implies that the flow is in the zero-flow state (Fig. 26).

To more quantitatively describe the behavior of the HV in the symmetry plane, the maximum of the $Q$-criterion, $Q_{\text{max}}$, in the symmetry plane is associated with the location $x_c, z_c$ of the core of the HV if the crossflow vorticity $\omega_y$ is positive. Here, $x_c$ is the distance from the core to the leading edge. An algorithm was developed that searches from the core location in the upstream and downstream direction to find the $x$ locations where $Q$ drops below $0.1Q_{\text{max}}$. The same procedure was applied to find similar bounds in the spanwise direction. The HV circulation was then computed as $\Gamma = \int \omega_y \, dA$, where $A$ was approximated as the rectangular area spanned by the streamwise and spanwise bounds. Figure 27 reveals that the HV is moving back and forth in a random fashion and experiencing strong fluctuations of both $Q_{\text{max}}$ and $\Gamma$. For time instances when the circulation is large, the HV is typically closer to the leading edge of the Rood wing. The frequency of the circulation fluctuations is roughly 0.13. Made dimensionless with the BL thickness upstream of separation at $x = -1, \delta = 0.88$, and freestream velocity, a frequency of 0.11 is obtained, which is just outside the range reported by Gand et al. [17] ($0.05 < f\delta/u_\infty < 0.1$).

Figure 28 provides instantaneous flow visualizations for times when the circulation attains maxima and minima. For the former, the HV is located close to $x = -0.1$, whereas for the latter the HV is noticeably absent. A strong HV implies that the flow is in the backflow state, whereas a weak or entirely missing HV implies that the flow is in the zero-flow state.

A time sequence that shows the development toward a strong HV at $t = 122.95$ and then back toward a weak HV at $t = 125.45$ is provided in Fig. 29. The flow visualizations indicate that lumps of
highly elevated turbulence are hitting the interaction region at random times and locations. For example, at $t = 119.95$, a region of elevated turbulence is impacting the left side (with respect to the view of the figure) of the leading-edge region. This event is followed by a significant strengthening of the HV as seen for $t = 122.45$ and 122.95.

Figure 30 provides a sequence that displays how a coherent HV is weakened by incoming BL turbulence. The coherent HV can be seen for $107.55 < t < 108.45$. For $t \geq 108.75$ a packet of elevated turbulence begins to impact the HV a little bit to the right of the symmetry plane (e.g., $t = 109.05$) and leads to a weakening of the right half of the HV. Later, at $t = 110.55$, a small region of elevated upstream turbulence interacts with the left half of the HV. Likely as a result of both events, the HV is weakened and moving closer toward the leading edge. For $t > 110.25$ a new HV is seen to develop farther

Fig. 27  Vortex core location, maximum $Q$-criterion, and circulation of horseshoe vortex.

Fig. 28  Instantaneous isosurfaces of $Q = 1$ and 100, and isocontours of crossflow vorticity $\omega$, in symmetry plane for time instances when circulation attains maxima (left) and minima (right).

Fig. 29  Instantaneous isosurfaces of $Q = 1$ for indicated time instances.
away from the leading edge. The present analysis stands out with respect to the earlier research by, e.g., Devenport and Simpson [1], Agui and Andreopoulos [11], and Sabatino and Smith [14] in considering instantaneous 3-D visualizations of the entire HSV system and the connection that is made to the HSV location and circulation.

D. Probability Density Function

Probability density functions (PDFs) for the simulation and experiment are provided in Figs. 31 and 32. For the LES, the PDF of the HV location in the symmetry plane, $x_c$, is shown. The experimental PDF is for the streamwise velocity in the interaction region. The PDFs are computed by splitting the range of the data sets into discrete intervals or bins. An integer counter for each bin is incremented when the data fall within the range of the associated interval. The integer number for each interval is then divided by the total number of data points.

Fig. 31  Probability density function of the streamwise HV core position (LES).

Fig. 32  Contours of nondimensional vorticity at two instances in time corresponding to a) the backflow mode and b) the zero-flow mode. c) PDF of streamwise velocity at $x = -0.13$ and $z = 0.013$ (experiment).
points to obtain the probability density. The PDF for the streamwise core position in Fig. 27 has a peak at about $x_c = -0.24$, which can be associated with the backflow mode, and a second peak at $x_c = -0.12$, which can be associated with the zero-flow mode. The experimental PDF has peaks at about $u/U_{ref} = -0.5$ and 0, which are related to the backflow and zero-flow mode, respectively. The PDFs are similar but cannot be directly compared because they were computed for different quantities.

IV. Effect of Fillet on Flowfield

A. Mean Flow

As shown by Devenport et al. [22], fillets can have an effect on the bimodal behavior. To investigate if this is also the case for the chosen Rood wing geometry and Reynolds number, additional simulations with circular endwall fillet with a radius of 0.1 (case F1) and 0.2 (case F2) were carried out. The setup of the simulations with fillet was the same as for the simulation without fillet (case NF). By comparing the results from the simulations with and without a fillet, the effect of the fillet on the mean flow and the bimodal behavior can be determined.

Isosurfaces of the $Q$-criterion computed from the time-averaged and instantaneous flowfields are provided in Fig. 33. The time averages indicate that the HV becomes stronger and moves further away from the leading edge as the fillet radius is increased. Because of the finite lengths of the time-averaging intervals, the time averages are not perfectly symmetric. A stronger HV in the mean implies that the instantaneous HV is stronger and/or that the HV is moving less. The instantaneous flow visualizations hint at similarly intense HVs, which suggests that the HV is moving less for the cases with fillet.

Isocontours of the time-averaged streamwise velocity in the symmetry plane in Fig. 34 show that as the fillet radius is increased, the reverse flow region at the bottom wall intensifies. The recirculation region also becomes thicker and more stretched out in the upstream and downstream directions. Isocontours of the streamfunction in Fig. 35 clearly outline the separated region. The core of the time-averaged HV is situated at $(x_c, z_c) = (−0.12, 0.042)$ for case NF, and then moves upstream and away from the wall as the fillet radius is increased: $(-0.15, 0.042)$ for case F1 and $(-0.21, 0.049)$ for case F2. Also, the streamlines surrounding the HV core become rounder, which implies that the HV is moving less. For the unfilleted Rood wing, a smaller secondary vortex with opposite sense of rotation is located at $(x, z) = (-0.014, 0.019)$. This secondary vortex is missing for cases F1 and F2.

Top-down views of the endwall colored by the magnitude of the skin-friction coefficient in Fig. 36 suggest that the HV gets weaker and/or moves farther away from the endwall as the fillet radius is increased. As for case NF, the skin-friction lines display a saddle point upstream of the leading edge. For cases F1 and F2, the saddle point is roughly located at $x = -0.8$ and $x = -0.7$, which is upstream of the saddle point position for the unfilleted airfoil ($x = -0.6$). This is consistent with the earlier observation that the HV moves upstream as the fillet radius is increased. Isocontours of the wall pressure coefficient in Fig. 37 reveal a small increase of the low-pressure regions near the maximum thickness of the airfoil, which suggests that the fillet reduces the corner separation.

B. Unsteady Flow

Using the same methods as before to quantitatively describe the behavior of the HV, the core location $x_c$ and circulation $Γ$ in the symmetry plane were extracted from the time-dependent flow data (Fig. 38). Without fillet (case NF), the circulation fluctuates widely between 0 and a maximum value of 0.1. Sudden jumps of the vortex core location occur when the circulation is low. These jumps can be attributed to the vortex detection method that always selects the strongest vortex. For example, near $t = 305$, a weakening vortex near the leading edge is replaced by a new stronger vortex far away from the leading edge. For case F1 the circulation exhibits similar but less frequent fluctuations than for case NF. For case F2 the unsteadiness is noticeably suppressed compared with the unfilleted airfoil. The mean HV core locations computed from the $x_c$ time averages (Table 4) roughly agree with the core locations in Fig. 35. The mean

![Fig. 33 Isosurfaces of $Q = 100$ for cases NF (left), F1 (center), and F2 (right). a) Time averages and b) instantaneous flowfields.](image)

![Fig. 34 Isocontours of streamwise velocity in symmetry plane for cases a) NF, b) F1, and c) F2.](image)
Fig. 35  Streamlines in symmetry plane for cases a) NF, b) F1, and c) F2.

Fig. 36  Isocontours of skin-friction coefficient magnitude and skin-friction lines obtained from time-averages for cases a) NF, b) F1, and c) F2.

Fig. 37  Isocontours of wall pressure coefficient for cases a) NF, b) F1, and c) F2.

Fig. 38  Vortex core location and circulation for cases a) NF and b) F1 and F2.
circulation is the largest for case F1, followed by cases NF and F2. As a measure for the overall flow unsteadiness, the standard deviations were computed for $220 < t < 245$ (NF), $18 < t < 44.4$ (F1), and $16 < t < 40$ (F2). With increasing fillet radius, the standard deviations are noticeably lowered. Finally, the period of the circulation fluctuations was computed (Table 4). Although the spectral resolution is poor, the present results indicate that the fillets reduce the HV unsteadiness and increase the mode switching frequency.

V. Conclusions

Turbulent junction flows are known to exhibit a bimodal behavior that is characterized by the more or less random switching between a zero-flow and backflow state [1]. The literature suggests that the bimodal behavior is triggered by turbulent BL events (such as hairpin vortices) that interact with the HV [11,12,14]. LESs and well-instrumented experiments were carried out for a generic turbulent junction flow geometry, the Rood wing airfoil. The Reynolds number for the simulations based on approach flow velocity and airfoil thickness was 7000. The BL thickness ahead of the junction was $0.11$ and thus nearly inside the range $< 0.0757 \text{ to } 0.0276 \text{ to } 0.0177 < 9.5$.

The simulations do not provide a clear answer to the question if the bimodal behavior results from an inherent instability of the interaction or from the interaction of upstream turbulent BL structures with the HV. In many instances, the presence of elevated upstream turbulence with the HV was observed to correlate with a downstream motion and strengthening of the HV. This observation is in agreement with Devenport et al. [22], who argue that the HV was observed to correlate with a downstream motion and strengthening of the HV. In many instances, the presence of elevated upstream turbulence was found to lead to a loss of coherence and weakening of the HV in agreement with Escauriaza and Sotiropoulos [18].

The Rood wing geometry was filleted by adding a circular radius of 10 and 20% of the maximum thickness at the endwall junction. In agreement with Devenport et al. [22], the fillets suppressed the bimodal behavior and reduced the junction flow unsteadiness. The present Rood wing simulations and experiments are in agreement with the published literature with respect to the mean flow and the observed unsteadiness. They do thus establish a basis for a later more detailed analysis of the correlation between the approach BL unsteadiness and the junction flow behavior. What makes the present analysis stand out with respect to the earlier research are the detailed instantaneous 3-D realizations of the entire HV system and the time histories of the vortex location and circulation. Future work will focus on a quantification of the upstream BL effect. In particular, the question will be addressed if a deterministic link exists between the bimodal behavior and incoming BL turbulence.

### Table 4 Mean and standard deviation of streamwise core location $x_c$ and circulation $\Gamma$ of horseshoe vortex as well as dominant period

<table>
<thead>
<tr>
<th>Case</th>
<th>$x_c$</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mode switching</th>
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</thead>
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<tr>
<td>NF</td>
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<td>0.0757</td>
<td>0.0276</td>
<td>0.0177</td>
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</tr>
<tr>
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<td>0.0167</td>
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<tr>
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<td>0.0250</td>
<td>0.0099</td>
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<td></td>
</tr>
</tbody>
</table>

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References


