GPU-accelerated large-eddy simulations of the NASA fan noise source diagnostic test benchmark

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Wall-modeled large-eddy simulations of NASA Fan Broadband Source Diagnostic Test (SDT) model are performed using the GPU-accelerated moving-mesh compressible flow solver charLES. Three different outlet guide vane (OGV) configurations (i.e., baseline, low count and low noise) are simulated under the approach condition. The full annulus of the fan and the OGVs, the nacelle and the entire test section are included in the computational domain to avoid numerical artifacts caused by artificial periodicity or domain truncation. The LES results are compared to available experimental data in terms of aerodynamic performance, unsteady flow fields and far-field noise, and show good overall agreement. In particular, the predicted sound power levels and the fan and stage performance match closely with the measurements for the three OGV configurations. The SDT configuration is also used to assess the solver scalability and increased computational throughput with GPU acceleration: for the present O(140) million cell mesh, the simulation results for 10 full rotations are obtained in approximately 6 hours on 40 standard GPUs.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>C</td>
<td>Blade chord</td>
</tr>
<tr>
<td>c</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
</tr>
<tr>
<td>P_t</td>
<td>Total pressure</td>
</tr>
<tr>
<td>T_t</td>
<td>Total temperature</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>x, y, z</td>
<td>Cartesian coordinates</td>
</tr>
<tr>
<td>η_ad</td>
<td>Adiabatic efficiency</td>
</tr>
<tr>
<td>γ</td>
<td>Specific heat ratio</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
</tr>
<tr>
<td>τ_wall</td>
<td>Wall shear stress</td>
</tr>
<tr>
<td>θ</td>
<td>Microphone geometric angle</td>
</tr>
<tr>
<td>∞</td>
<td>Free-stream property</td>
</tr>
<tr>
<td>ref</td>
<td>Reference value</td>
</tr>
<tr>
<td>avg</td>
<td>Time-averaged quantity</td>
</tr>
<tr>
<td>rms</td>
<td>Root-mean-square quantity</td>
</tr>
</tbody>
</table>

I. Introduction

Lowering noise radiation continues to be one of the primary targets of the engine and aircraft designs. The fan noise Source Diagnostic Test (SDT) was one of the research efforts for investigating noise generation mechanisms in modern high bypass ratio turbofan engine. It was developed by a cooperative effort between NASA and GE Aircraft Engines in early 2000s. As shown in Figure 1, the model includes a single-stage fan consisting of a fan (rotor) and outlet guide vanes (OGV) within a flight-type nacelle. Two rotors and three OGV configurations (baseline, low count and low noise) were tested at various operating conditions. The experiment was conducted in the anechoic NASA Glenn 9′ × 15′ Low Speed Wind Tunnel, as shown in Figure 1(a). The fan and stage performance was measured through total pressure/total temperature...
rakes downstream of the fan and OGVs, respectively [1]. Flow field details were acquired between the rotor and OGV by a laser Doppler velocimetry (LDV) system (see Figure 1(b)) [2]. Far-field acoustic data were recorded by translating or wall-mounted microphone probes (see Figure 1(c)) at three operating conditions: approach (61.7% design speed), cut-back (87.5% design speed) and take-off (100% design speed) [3].

Over the years, the SDT configuration has been employed as a benchmark for computational fluid dynamics and aeroacoustics research. There have been computational efforts in simulating the SDT fan with different levels of numerical fidelity, from unsteady Reynolds-averaged Naiver-Stokes (uRANS), improved delayed detached-eddy simulation (IDDES) to wall-modeled/wall-resolved large-eddy simulations (WMLES/WR-LES). Kholodov and Moreau [4] simulated the rotor only SDT at approach condition using wall-modeled LES code AVBP and identified the contributions of different blade regions to the radiated sound. Fiore et al. [5] employed wall-resolved LES with a phase-lagged assumption to calculate the three OGV configurations at three operating conditions and assessed the losses generated in these settings, but no acoustic results were presented. Due to high computational cost, these high-fidelity simulations were limited to single rotor/OGV blade passage with periodic boundary conditions applied in the circumferential direction.

Attempts to include the full annulus were also reported in recent years. Shur et al. [6], and Suzuki et al. [7, 8] simulated the baseline OGV configuration at approach and takeoff conditions using hybrid uRANS/IDDES method on a block-structured grid with approximately 140M cells. The predicted broadband noise was within 3dB in the approach condition but larger underprediction was observed in the takeoff condition. The Lattice-Boltzmann/very-large-eddy simulation (LBM/VLES) method was utilized to compute the full-stage whole annulus SDT for three OGV configurations at the approach condition by Casalino et al. [9]. The simulations were performed using the commercial solver EXA PowerFLOW on Cartesian grids up to 261M fine equivalent voxels (FEVs). Reasonable acoustic predictions were reported for the baseline and low noise OGVs. In these simulations, due to the relatively coarse resolution in blade boundary layers, a trip on the suction side of the blade was used to trigger boundary layer transition and improve the velocity spectra predictions. In a follow-up study, three different versions of PowerFLOW were used to simulate the low noise OGV configuration at the approach condition [10]. The version with improved scale-resolving capabilities was able to predict velocity spectra with better accuracy than the other two versions, and no solid trip on blade surface was needed.

In the present work, the SDT fan configuration is simulated for the three OGV configurations at the approach condition using the GPU-accelerated moving-mesh compressible flow solver “charLES” developed at Cascade Technologies, now part of Cadence Design Systems. The wall-modeled simulations include the full annulus, whole stage of the fan and OGV. The entire test section of the wind tunnel is included in the computational domain as well to minimize the numerical artifacts caused by domain truncation. Both stationary and rotating parts of the grid are generated based on the computation of 3D Voronoi diagrams,
with conformal mesh around the blade surface to respect the original geometries. Details of the configuration and numerical setup are reported in Section II. Comparisons of the experimental and simulation results are presented in Section III. Finally, computational cost, solver scalability and increased throughput achieved with GPU acceleration are discussed in Section IV.

II. NASA SDT fan configurations and simulation setup

A. SDT configurations

Two rotors, namely “R4” and “M5” operating at 12,657 and 14,064 corrected RPM respectively, were tested, and the former is simulated in the present study. The OGV has three distinct designs as shown in Figure 2. The “baseline” configuration consists of 54 narrow chord vanes. The “low count” and “low noise” configurations reduce the blade count to 26 but increase the chord length from 1.57 in to 3.26 in. In addition, the vanes in the low noise configuration are at a 30° aft sweep angle [1]. The latter two configurations with reduced vane count were designed to study the impact of vane geometry on noise source distribution and far-field sound reduction. The fan/OGV configurations, operating conditions and the availability of experimental measurements are summarized in Table 1.

![SDT fan configurations](image)

Figure 2: SDT fan with three different OGV configurations.

<table>
<thead>
<tr>
<th>Info source</th>
<th>Fan type</th>
<th>OGV configuration</th>
<th>operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R4</td>
<td>M5</td>
<td>base</td>
</tr>
<tr>
<td>Experiment</td>
<td>far-field noise</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>LDV</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>blade pressure</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 1: SDT fan configurations and operating conditions.

B. Solver

In the present work, wall-modeled LES of the SDT fan for the three OGV configurations at the approach condition are performed with the Cascade’s GPU-accelerated moving-mesh compressible flow solver “charLES” developed at Cascade Technologies, now part of Cadence Design Systems.

For the current version of the software, the unstructured mesh is generated through the computation of Voronoi diagrams [11]. As a way of partitioning, a Voronoi diagram divides space into elements surrounding a given set of forming points with each element defined as the region of space closest to a forming point relative to all other forming points. It enables highly scalable mesh generation, since the global mesh is uniquely defined, yet each individual cell can be constructed with only local information. The mathematical properties of Voronoi diagrams provide computational efficiencies for both robust and flexible mesh generation, as well as for flow solvers. Importantly, the Voronoi paradigm reduces the problem of mesh generation to the much simpler problem of specifying the generating point locations, i.e. the locations where the solution will be sampled. The actual mesh (volumes, faces, topology, neighbor connectivity) is simply a unique mathematical consequence of this choice based on the definition of the Voronoi diagram. This dramatically simplifies the
control over local mesh resolution - an important consideration for automation and high-fidelity simulations. Additionally, the discretization of the boundary surface (faceting/triangulation of the surface) is independent from the near-boundary mesh resolution, allowing for arbitrary coarsening or refinement relative to the local surface length scales. The impact of leveraging these benefits in mesh generation is a dramatic reduction in the time and human interaction required to generate quality meshes for high-fidelity applications. The flexibility and simplicity of the Voronoi meshing approach make it an attractive paradigm for mesh motion. At any given time step, a single, conformal grid (from the collection of deformable Voronoi diagrams) is present that allows for a conservative discretization.

Figure 3: Illustration of 2D Voronoi diagrams given a set of generating points (blue dots). The faces (black edges) are perpendicular bisectors between the generating points. (b) shows the clipped Voronoi diagram for the same generating points, where the bounding surface (red lines) “clips” the exterior cells but has no effect on internal cells whose extents are defined only by generating points. Note that the spatial distribution of the generating points is formally independent of the bounding surface.

For the calculations performed here, the mesh motion is restricted to isolated rotating bodies. This permits two simplifications regarding the mesh motion that allows for substantial speedup: 1) that the interface is effectively “sliding” (a rotating disk for instance) and 2) that there are no appearing or disappearing degrees of freedom (that might be encountered if the total domain volume was a function of time as would be the case for a valve opening). The simplification to “sliding” interfaces is sufficiently general to tackle the problems with rigid body rotations, such as rotating rotor & propeller flows. Under these simplifications, the mesh rebuilding step reduces to performing an update of the Voronoi diagram faces on the moving-stationary interface only. In Figure 4, the magenta line segment represents an interface face and the red dot is the cell center in the rotating part next to the face. When the part rotates, the face is cut by different neighbors encountered in the stationary part (blue dots).

Figure 4: Rotating interface at two consecutive time steps $t_0$ and $t_1$. 


The solver employs a low-dissipation, nonlinearly stable numerical scheme. An extended gradient operator is constructed for all interior cells, which is formally second order accurate (in an $L_\infty$ sense) on arbitrary meshes with small dispersive errors. An efficient one-sided compact gradient operator is used to treat the stationary-moving part interfaces. Away from the interface, the spatial operators in the stationary region are left unchanged while the those of the moving region are linearly transformed. The full discretization is skew-symmetric and conservative by construction. Due to its flexibility in building part interfaces and its numerical accuracy, the solver is particularly suitable for turbomachinery applications and aeroacoustic simulations.

C. Computational domain and boundary conditions

The setup of the SDT fan experiment is depicted in Figure 5. The designed speed of the fan is 12,657 RPM with a tip Mach number of 1.085. The blade-passing frequency is thus 4641 Hz. Under the approach condition, the fan operates at a reduced rotational speed of 7,809 RPM, which is 61.7% of the designed speed, and a tip Mach number of 0.669.

![Figure 5: The experimental setup of the NASA SDT fan (from ref. [3])](image)

The computational domain include the whole stage, full annulus, as well as the entire test section of the wind tunnel to minimize the numerical artifacts caused by domain truncation. At the inlet, uniform flow at freestream Mach number $M_\infty = 0.1$ with ambient conditions $p_\infty = 100,619$ Pa and $T_\infty = 287.57$ K are specified to match the standard day sea level total pressure $p_{\text{ref}} = 101,325$ Pa and total temperature $T_{\text{ref}} = 288.15$ K conditions. Note that in the experiment, the aerodynamic quantities are measured at $M_\infty = 0.05$ and the acoustics data are acquired at $M_\infty = 0.1$, and both are corrected to the standard day sea level conditions. The simulations are all performed at $M_\infty = 0.1$ and corrected to the sea level conditions.

A Navier-Stokes characteristic boundary condition (NSCBC) with specified outlet pressure is employed at the outlet to implement a non-reflective outlet boundary condition. A slip wall boundary condition is used on wind tunnel walls and an adiabatic wall-stress modeling based on the equilibrium boundary layer assumption [12, 13] is applied to all other internal surfaces. No geometric or numerical trip is used on blade surfaces. Outside the region marked by the orange rectangle as shown in Figure 6(a), a sponge layer is applied to damp out acoustic waves to avoid spurious reflections at the boundary of the computational domain. The Vreman [14] sub-grid model is used to account for the physical effects of the unresolved turbulence on the resolved flow.
The far-field noise is computed using the frequency-domain permeable formulation [15] of the Ffowcs Williams & Hawkings [16] (FW-H) equations. Presently, the noise predictions are done as a post-processing step and details of the current implementation of FW-H solver are available in appendix of Brès et al. [17]. Two FW-H surfaces for far-field noise predictions are shown in Figure 6(a). The surface in blue, s1, is a closed surface covering a wide region around the turbofan. The method of end-caps [18] on the downstream part of FW-H surface is used to minimize spurious noise from wake and vortices crossing the surface. The surface in red, s2, is an open but tight surface that is much closer to the turbofan surfaces.

The computational domain is divided into stationary and moving parts by planar interfaces as shown in Figure 6(b). The rotating part (green) contains the rotor and the entire spinner. The nacelle interior surface is cut by the interfaces and part of it is included in the moving part. The zero velocities on it is specified in the boundary condition.

D. Acoustic calculation

The experimental setup for acoustic measurement is depicted in Figure 7. The acoustic signal is recorded by a translating microphone probe traversing along a sideline 2.25 m away from the fan axis. The geometric angle $\theta$ between the line from the rotor center to the microphone and the rotation axis varies from $30^\circ$ to $140^\circ$ in $5^\circ$ increment. In addition, there are three fixed microphone probes mounted at geometric angles $140^\circ$, $150^\circ$ and $160^\circ$ to acquire aft acoustic data. For the numerical data, the narrowband spectra are predicted with the FW-H approach at the microphone locations for 18 azimuthal angles and then ensemble-averaged to exploit the symmetry and achieve better statistical convergence. A bin-averaged power spectral density (PSD) is computed from the narrowband spectra, with a bin size $\Delta f = 59$ Hz, matching the experimental data bandwidth. The sound power levels (PWL) are computed from the PSD on the traversing microphones and fixed microphones using

$$\text{PWL}(f) = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} 2\pi R^2 \sin\theta \frac{[1 + M_\infty \cos\theta]^2 \text{PSD}(f, \theta)}{2 \rho_\infty c_\infty} d\theta,$$

where $R$ is the radius measured from the rotor center to the microphone. Similar to the process to evaluate OASPL, the overall sound power level (OAPWL) can be computed by integrating the PWL over a specified frequency range.

E. Computational meshes

For the present study, three meshes are considered for the low noise OGV configuration under approach condition. The coarse mesh has 73 million control volumes (Mcv). The grid spacing is 1 mm on the internal surfaces, 2 mm on the nacelle exterior and 2 mm inside nacelle (Figure 8(a)). The mesh leverages Voronoi meshing to coarsely represent tip gap, i.e., the minimum grid spacing, 1 mm, is approximately 2 times of the
Figure 7: Experimental setup for acoustic measurement [3].

(a) cut through the rotation axis

(b) axial cut.

Figure 8: Coarse mesh with 73 Mcv.

(a) cut through the rotation axis

(b) axial cut

Figure 9: Refined mesh with 190 Mcv.
nominal tip gap 0.52 mm. The second and third meshes are refined meshes based on the coarse mesh. They employ similar refinement windows in the volume and near-wall grid spacing on all the internal surfaces reduced from 1 mm to 0.5 mm. In these meshes, the grid spacing on the casing is nearly the same as the tip gap. The only difference between these two meshes is the packing of the seeds: the second mesh uses hexagonal close-packed (HCP) seeding, the same as the coarse mesh, and has a total number of 190 Mcv (see Figure 9); the third mesh uses Cartesian packing and results in a mesh of 142 Mcvs.

III. Comparisons of experimental and numerical results

A. Grid sensitivity study

The low noise OGV at the approach condition is simulated on the coarse and refined meshes. Figures 10 and 11 show the Mach number in a plane cutting through the rotation axis as well as the wall shear stresses on the rotor, stator, hub and nacelle, for the 73 Mcv and 190 Mcv mesh, respectively. The internal surface resolution for both cases is presented on the figures as reference. Note that the results on the 142 Mcv mesh show negligible differences and are not reported. Qualitatively, the flow results look similar and the main differences are observed for laminar to turbulent boundary layer transition on the nacelle interior surface upstream of the fan. The yellow dashed lines in the figures approximately mark the transition positions. When the mesh is refined on the interior surface, the transition happens closer to the nacelle inlet but appears to have limited impact on the flow further downstream.

![Figure 10](image1.png)
(a) Internal flow and blade surfaces  
(b) Nacelle interior surface

Figure 10: Visualization of the flow Mach number and surface shear stress for the NASA fan SDT from the GPU-accelerated charLES simulation on the coarse 73 Mcv mesh.

![Figure 11](image2.png)
(a) Internal flow and blade surfaces  
(b) Nacelle interior surface

Figure 11: Visualization of the flow Mach number and surface shear stress for the NASA fan SDT from the GPU-accelerated charLES simulation on the refined 190 Mcv mesh.

The flow velocities in the experiment were measured using a laser Doppler velocimeter (LDV) system. The data were acquired between the fan and the OGVs at two stations, LDV1 and LDV2, which are 3.12 and 6.49 inches downstream from the tip trailing edge of the rotor blades respectively. The LES data are collected
at the same locations. The statistics, mean and rms, of the axial and tangential velocities are compared
against the experimental LDV measurements, as shown in Figures 12 and 13. A reasonable agreement, in
terms of the velocity distribution and the magnitude of the statistics, is observed for the coarse mesh. The
LES results are further improved by the grid refinement for the 190 Mcv mesh and an even better agreement
with the experimental measurements is obtained on the refined mesh. Here, the results on the 142 Mcv mesh
show again negligible differences between the two refined grids and are not reported.

The flow statistics are presented in Table 2. The mass flow rate is corrected using

\[ \dot{m}_c = \dot{m} \sqrt{\frac{P_t}{P_{ref}}} \]  

(2)

and the adiabatic efficiency is calculated via

\[ \eta_{ad} = \left( \frac{P_t}{P_{inf}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \]  

(3)

where \( \gamma = 1.4 \) is the specific heat ratio. In the simulations, the total conditions match the standard day sea
level conditions to the level that the correction factor for the mass flow rate is within 0.05% from unity. Note
that in the table the total pressure and temperature ratios have been rounded to the closest numbers with
four digits while the efficiencies are calculated using the numbers with full precision. Good agreement with
the experimental measurement is obtained on the coarse mesh. Overall, the differences between the three
meshes are small, indicating a solution convergence with increasing resolution for the predicted aerodynamic
performances. Compared to the experimental values, most quantities have been slightly improved on the
refined meshes, with again negligible differences between the 142 Mcv and 190 Mcv grids.

<table>
<thead>
<tr>
<th>Case</th>
<th>Fan ( P_t ) ratio</th>
<th>Stage ( P_t ) ratio</th>
<th>Fan ( T_t ) ratio</th>
<th>Stage ( T_t ) ratio</th>
<th>Fan ( \eta_{ad} )</th>
<th>Stage ( \eta_{ad} )</th>
<th>( \dot{m}_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA exp.</td>
<td>1.159</td>
<td>1.153</td>
<td>1.049</td>
<td>1.049</td>
<td>0.889</td>
<td>0.857</td>
<td>26.44 kg/s</td>
</tr>
<tr>
<td>LES (73 Mcv)</td>
<td>1.160</td>
<td>1.151</td>
<td>1.049</td>
<td>1.049</td>
<td>0.892</td>
<td>0.848</td>
<td>26.36 kg/s</td>
</tr>
<tr>
<td>relative error</td>
<td>0.10%</td>
<td>-0.11%</td>
<td>-0.05%</td>
<td>-0.05%</td>
<td>0.4%</td>
<td>-1.0%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>LES (142 Mcv)</td>
<td>1.162</td>
<td>1.154</td>
<td>1.049</td>
<td>1.049</td>
<td>0.898</td>
<td>0.856</td>
<td>26.55 kg/s</td>
</tr>
<tr>
<td>relative error</td>
<td>0.25%</td>
<td>0.07%</td>
<td>-0.03%</td>
<td>-0.03%</td>
<td>1%</td>
<td>-1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>LES (190 Mcv)</td>
<td>1.161</td>
<td>1.153</td>
<td>1.048</td>
<td>1.048</td>
<td>0.898</td>
<td>0.856</td>
<td>26.50 kg/s</td>
</tr>
<tr>
<td>relative error</td>
<td>0.18%</td>
<td>0.01%</td>
<td>-0.05%</td>
<td>-0.05%</td>
<td>1%</td>
<td>-1%</td>
<td>0.22%</td>
</tr>
</tbody>
</table>

Table 2: Fan and stage performance for the low noise OGV under approach condition on the coarse and
refined meshes.

The spectra of PWL, converted in dB/Hz relative to \( \dot{W}_{ref} = 1 \times 10^{-12} \) Watts, are reported in Figure 14
for the experiment and the LES on the coarse and refined meshes. The far-field noise computed from the
two FW-H surfaces considered in the present work show similar results, with slightly better predictions in
the high frequency range for the \( s2 \) surface closer to the nacelle. Therefore, only the results for the FW-H
\( s2 \) surface are reported in the following sections. The expected cutoff frequency for that FW-H surface in
the 2 mm resolution region is \( f_{cutoff} \approx 22 \) kHz assuming 8 pts per wavelength are needed for resolving
the acoustics. While the results for the coarse mesh show reasonable agreement, the predictions are further
improved in both low- and high-frequency range with near-wall grid refinement. Both refined meshes predict
good overall results for tonal and broadband noise up to the expected cutoff frequency, with slight under-
prediction of about 2 dB at that frequency. The BPF tones and the \(-7/3\) spectral roll-off in the inertial
subrange are also well captured by the numerical calculations.

Based on this preliminary grid resolution study, the refined mesh with 142 Mcv is down-selected to
complete the simulations and analysis for the other OGV configurations.

B. Influence of OGV configurations on performance

Figure 15 shows the instantaneous flow Mach number and wall shear stresses \( \tau_{wall} \) on the rotor, stator,
hub and nacelle, for the baseline, low count and low noise OGV configurations at the approach condition.
Figure 12: Comparison of the experimental data and LES results at the LDV1 station.
Figure 13: Comparison of the experimental data and LES results at the LDV2 station.

(a) Axial velocity statistics

(b) Tangential velocity statistics
Figure 14: Comparisons of the sound power level (PWL) for the low noise OGV configuration under approach condition (61.7% design speed): Experiment (−▪−); LES for 73 Mcv ( ), 142 Mcv ( ) and 190 Mcv ( ) meshes. The vertical dashed lines represent the BPF and first four harmonics. The thick black line corresponds to the theoretical decay of pressure fluctuations in isotropic turbulence with $-7/3$ slope.

For all the visualizations, the color range is kept constant, i.e., from 0 (black) to 0.8 (white) for the Mach number, and from 0 (black) to 150 Pa (white) for $\tau_{wall}$. As discussed in section A, the boundary layer on the nacelle interior transitions from laminar to turbulent within the first $O(0.1)$ m from the nacelle inlet. Overall, the present wall-modeled results suggest that the transition is largely independent of the OGV configurations. Additional near-wall resolution on the nacelle interior surface would be needed to confirm this observation. One approach currently under investigation is the use of anisotropic strand meshes with modest aspect ratio appropriate for LES to reduce the total cell count while maintaining adequate surface resolution. Qualitatively, the flow inside the nacelle upstream of the fan look similar for all three OGV configurations, which is consistent with the results for the fan performance discussed in the next section. Downstream of the stator, the flow is straighten out by the OGV as intended. The main visible differences are the size and spacing of the turbulent wakes after the baseline OGV (54 vanes), the low count OGV (26 larger vanes) and the low noise OGV (same 26 larger vanes with 30° stator aft sweep angle).

The summary of the stage performances are presented in table 3 for the three OGV configurations. As discussed by Hughes [1], the uncertainties on the measurements are ±0.0003 for pressure ratio, ±0.001 for temperature ratio and ±0.003 for adiabatic efficiency. While the fan performance was measured in the wind-tunnel with all three OGV configurations, the changes in fan performance for the different OGV were reported as insignificant [1]. This observation was reproduced in the present simulations: the variations of the LES results with OGV were order ±0.0001 for the fan pressure ratio, temperature ratio and adiabatic efficiency. Therefore, the experimental and LES results for the fan performance are reported only for the low noise OGV configuration in table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Stage $P_t$ ratio</th>
<th>Stage $T_t$ ratio</th>
<th>Stage $\eta_{ad}$</th>
<th>$m_c$ (kg/s)</th>
<th>OAPWL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline OGV (NASA exp.)</td>
<td>1.154</td>
<td>1.049</td>
<td>0.860</td>
<td>26.54</td>
<td>125.7</td>
</tr>
<tr>
<td>Baseline OGV (LES)</td>
<td>1.154</td>
<td>1.049</td>
<td>0.856</td>
<td>26.53</td>
<td>124.2</td>
</tr>
<tr>
<td>Low count OGV (NASA exp.)</td>
<td>1.154</td>
<td>1.049</td>
<td>0.861</td>
<td>26.54</td>
<td>126.9</td>
</tr>
<tr>
<td>Low count OGV (LES)</td>
<td>1.154</td>
<td>1.049</td>
<td>0.860</td>
<td>26.55</td>
<td>124.6</td>
</tr>
<tr>
<td>Low noise OGV (NASA exp.)</td>
<td>1.153</td>
<td>1.049</td>
<td>0.857</td>
<td>26.44</td>
<td>124.1</td>
</tr>
<tr>
<td>Low noise OGV (LES)</td>
<td>1.154</td>
<td>1.049</td>
<td>0.856</td>
<td>26.55</td>
<td>122.7</td>
</tr>
</tbody>
</table>

Table 3: Comparisons of the stage performance and radiated noise for the baseline, low count and low noise OGV configurations under the approach condition (61.7% design speed) between the experimental measurement and the LES on the 142 Mcv mesh.
Figure 15: Visualization of the flow Mach number and surface shear stress for the NASA fan SDT with baseline, low count and low noise OGV configurations at approach condition (61.7% design speed), from the GPU-accelerated charLES simulation on the 142 Mcv mesh.
Overall, the comparisons show good agreement between measurements and numerical predictions across all OGV configurations. In particular, all fan and stage total temperature ratio match very well, with less than 0.2% relative error. In the experiment, the assumption was made that there is no loss in total temperature across the OGVs and therefore the total temperature data from the fan performance rakes were used in the calculations of the stage adiabatic efficiency [1]. This assumption is confirmed in the simulations: at a given operating condition, the fan and stage $T_t$ ratios are nearly identical and independent of the OGV configuration.

Although the relatively coarse resolution in the fan blade tip gap and rotor surface might not be sufficient to fully capture the flow in the tip gap and/or the laminar-turbulent transition on the blade, the stage total pressure ratio and corrected mass flow rate $\dot{m}_c$ are all within 0.5% relative error for the three OGV configurations. For the adiabatic efficiency, the present conditions lead to both small numerator and denominator in Equation (3). Therefore, very small differences in $P_t$ or $T_t$ ratio can lead to larger discrepancies in $\eta_{ad}$. Still the correct trends are captured and the LES and the experimental adiabatic efficiencies are typically matched with less than 0.5% relative error.

C. Influence of OGV configurations on acoustics

Following the procedure described in Section II, the sound power level (PWL) is computed in dB/Hz for all the simulations and compared to the experimental measurements in Figure 16. Note that the spectra is displayed up to a very high frequency of 30 kHz and that the estimated cutoff frequency for the FW-H data is $f_{cutoff} \approx 22$ kHz. The fan blade passage frequency (BPF) is 2863 Hz for the approach condition. The main BPF and the first 4 harmonics are displayed on the figures by the dashed vertical lines. As recommended by the NASA experimentalists, the spectral levels below about 1.2 kHz are ignored since the signal contains jet noise associated with the bypass stream as well as extraneous rig noise.

Overall, the LES results show good comparisons with the measurements in terms of both broadband noise and BPF tone amplitude and frequencies. For some cases, there is a slight under-prediction in the high-frequency range. Additional work is being considered on sub-grid scale acoustic modeling and additional grid refinement to improve these predictions. Nevertheless, the simulations accurately capture the noise mitigation effects of the low noise OGV at this condition: the OAPWL (computed for $1200 \leq f \leq 30000$ Hz) of the low noise OGV is reduced by $\approx 2$ dB compared to the baseline and low count OGV, both in the experiments and simulations (see table 3).

IV. Solver scalability and GPU acceleration

While all the previous simulations used the GPU-accelerated version of the moving-mesh compressible flow solver charLES, a CPU-based version is also available. An additional simulation of the SDT fan benchmark was performed on CPUs for the refined case with 142 Mcv, and the results are nearly statistically identical, confirming the accuracy and repeatability for both versions. Here, it is important to note that the GPU implementation utilizes mixed-precision, in-house linear solvers and different memory access patterns to fully leverage the GPU memory bandwidth. Noise serves as a sensitive metric for assessing the accuracy of the GPU-accelerated implementation.

A scalability study was performed for both CPU-based and GPU-accelerated versions on the solver on the 190 Mcv mesh and the results are reported in Figure 17. The computations were performed without I/O on count ranging from 1,280 to 32,000 CPUs (AMD 7H12 Rome processors, 128 core/node), and from 20 to 60 GPUs (Nvidia V100 PCIe, 32 GB). Here, the moving-mesh compressible charLES solver displays good strong scaling up to a load of 10,000 cv per core and remains at about 70% scalability at 32,000 CPUs for load as low as approximately 6,000 cv per core. Likewise, the GPU-accelerated solver scales nearly perfectly to 60 GPUs, corresponding to a loading of approximately 3.1 Mcv per GPU. Improvement in the scalability and additional increase in throughput is anticipated with the ongoing solver and I/O optimization leveraging newer generation of GPU hardware with GPU direct communication protocols. For this configuration, each V100 GPU is found to be equivalent in throughput to $O(600)$ CPU cores, which is similar to the equivalence observed for the moving-mesh compressible flow solver charLES on other HPC systems.

In terms of computational cost for the complete analysis with all the I/O and diagnostics, the simulation of the SDT fan benchmark at approach conditions on the 142 Mcv mesh was performed on 4096 CPUs (AMD 7H12 Rome processors) and required approximately 100,000 CPUh per 10 full rotations of data collection.
Figure 16: Comparisons of the sound power levels (PWL) for the baseline, low count and low noise OGV configurations under the approach condition (61.7% design speed): Experiment (-----); LES (-----) on 142 Mcv mesh. The vertical dashed lines represent the BFP and first four harmonics.
Wall-modeled large-eddy simulations of the NASA SDT fan benchmark are performed with the GPU-accelerated moving-mesh compressible flow solver charLES developed at Cascade Technologies, now part of Cadence Design Systems. Three different OGV configurations, i.e., baseline, low count and low noise, are simulated at the approach condition where the fan operates at a reduced rotational speed of 7,809 RPM, which is 61.7% of the designed speed. The full annulus of the fan and the OGVs, the nacelle and the entire test section is included in the computations to avoid numerical artifacts caused by artificial periodicity or domain truncation. The unstructured meshes for both stationary and rotating parts are generated through the computation of Voronoi diagrams, which is a robust and efficient paradigm for mesh motion.

An initial grid sensitivity study is conducted and shows that although the coarse mesh with 73 M cells already results in reasonable predictions of the flow field, more accurate flow and acoustic predictions are obtained on a 142 M cells mesh with additional near-wall surface refinement. The refined mesh is down-selected and the results of the simulations of all three OGV configurations are compared to available experimental data. Despite the relatively modest mesh count and limited resolution on the fan blade, the OGV surface and in the tip gap (i.e., 1-2 cells), the comparisons show good overall agreements. In terms of aerodynamics, the fan and stage performance for the three OGV configurations matches closely with the experimental measurements. The mean and root mean square of the inter-stage flow velocities are compared to the measurements using a laser Doppler velocimeter and good agreement is observed. In terms of aeroacoustics, good comparisons of the sound power levels between the simulation and experimental data are also obtained for the BPF tone frequency and amplitude and broadband noise up to the grid cutoff frequency of 22,000 Hz. In particular, the trend of reduction of tonal and broadband noise due to the design of the OGVs is captured, consistent with the experimental observations: the overall sound power level is reduced by $\mathcal{O}(2)$ dB with the low noise OGV in both experiment and simulation.

The SDT fan benchmark configuration is also used to investigate scalability and performance of the com-
pressible flow solver charLES for both the CPU-based and GPU-accelerated versions. Simulations without I/O are performed on the 143 Mcv grid for counts ranging from 1,280 to 32,000 CPUs (AMD 7H12 Rome processors), and from 20 to 60 GPUs (Nvidia V100 PCIe). The present solver displayed good strong scaling on both CPUs and GPUs, with a throughput of $O(600)$ equivalent CPU cores per V100 GPU. Using the high throughput provided by the GPU acceleration, the simulation turn-around time for the collection of 10 full rotations is reduced from days on several thousand cores to a few hours on a modest GPU count. Future work will focus on I/O performance improvement and optimization in the GPU-accelerated solver, including other approaches to reduce data I/O for acoustic calculations.

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**References**


