GPU-accelerated large-eddy simulations of supersonic jets from twin rectangular nozzle

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Large eddy simulations of supersonic jets from a twin rectangular nozzle are performed with the GPU-accelerated version of Cascade’s “charLES” compressible flow solver. Comparisons of the numerical noise predictions with near-field and far-field microphone measurements show good agreement for the screech tone frequency, broadband spectra and overall sound pressure levels. For the screech tone amplitude, the agreement is further improved when the reflective surfaces upstream of the nozzle exit are modified in the computational domain to account for the thick acoustic foam covering these surfaces in the wind-tunnel. Such modifications and efficient exploration of the nozzle design space are made possible by the increased computational throughput with the GPU-accelerated solver: for the present \( O(100) \) million cell mesh and relatively long noise data collection of 2000 acoustic time units, the simulation results are obtained in about 12 hours on 30 standard GPUs.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( c )</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>Mesh resolution</td>
</tr>
<tr>
<td>( D_e )</td>
<td>Area-based equivalent nozzle diameter</td>
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<tr>
<td>( dt )</td>
<td>Time step</td>
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<tr>
<td>( f )</td>
<td>Frequency</td>
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<td>( h )</td>
<td>Nozzle height</td>
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<tr>
<td>( M )</td>
<td>Mach number</td>
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<tr>
<td>( NPR )</td>
<td>Nozzle pressure ratio</td>
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<td>( NTR )</td>
<td>Nozzle temperature ratio</td>
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<td>( p )</td>
<td>Pressure</td>
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<td>( r )</td>
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<td>( Re )</td>
<td>Reynolds number</td>
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<td>( St )</td>
<td>Strouhal number ( fD_e/U_j )</td>
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<tr>
<td>( \theta )</td>
<td>Polar angle</td>
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<tr>
<td>( T )</td>
<td>Temperature</td>
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<tr>
<td>( t )</td>
<td>Time</td>
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<tr>
<td>( U_j )</td>
<td>Mean streamwise jet velocity</td>
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<tr>
<td>( w )</td>
<td>Nozzle width</td>
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<tr>
<td>( \Delta t )</td>
<td>Sampling period</td>
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<tr>
<td>( \phi )</td>
<td>Azimuthal angle</td>
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<tr>
<td>( \rho )</td>
<td>Density</td>
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Subscript

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<tr>
<td>( \infty )</td>
<td>Free-stream property</td>
</tr>
<tr>
<td>( t )</td>
<td>Total (stagnation) property</td>
</tr>
<tr>
<td>( j )</td>
<td>Fully-expanded jet conditions</td>
</tr>
<tr>
<td>( \text{sim} )</td>
<td>Simulation quantity</td>
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<tr>
<td>( \text{exp} )</td>
<td>Experimental quantity</td>
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I. Introduction

Despite intensive research, the reduction of jet engine noise remains a theoretically and technologically challenging problem. Detailed measurements in full-scale engines are costly and difficult, and most lab facilities are limited to smaller scale jets at lower temperatures. While simulations can now accurately predict the acoustic radiation from complex nozzles at realistic conditions, reducing time-to-solution and computational costs are a priority to bring nozzle design optimization within reach [1].

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One potential path forward is to utilize recent developments in high performance computing (HPC) where accelerated architectures (e.g., graphics processing units (GPUs), co-processing units) have become increasingly prevalent in contemporary HPC systems. Some jet simulations have already been performed on GPUs by Markesteijn, Semiletov & Karabasov [2, 3, 4, 5], and showed promising results in terms of performance. Recently, Cascade Technologies has been developing a GPU-accelerated version of its flagship large eddy simulation (LES) software “charLES” that optimally leverages new GPU-accelerated HPC architectures for predictive, fast, and cost-efficient simulations of turbulent flows. Compared to traditional CPU-based HPC approach, a significant reduction in computational cost (or increase in computational throughput) has been observed [6], up to more than an order of magnitude, depending on the configuration.

This present study is part of a larger collaborative effort with Caltech, University of San Diego (UCSD) and Ohio State University (OSU) to exploit experimental measurements, large eddy simulation and data-driven techniques, in pursuit of fundamental understanding of jet noise actuation as well as high-fidelity modeling of complex nozzle geometries with actuation. The LES work is a continuation of previous (CPU-based) simulation of Brès et al. [7] and focuses on supersonic jet from the twin rectangular nozzle shown in figure 1 at the baseline conditions (i.e., without plasma actuation) matching the experiment at OSU [8, 9]. The configuration is complex, with a large flow region of interest and an extensive transient LES database required for data-driven analysis. It is therefore demanding in terms of computational resources and a logical candidate to demonstrate the benefits of GPU computing to speed up the turnaround time of the simulation and LES data acquisition.

Another important feature in this configuration with imperfectly expanded supersonic jets is the presence in the pressure spectra of high-intensity tones at distinct frequencies associated with screech. As originally described by Powell [10], jet screech is a resonance phenomenon characterized by a flow-acoustics feedback loop with four components: Kelvin-Helmholtz instability waves in the shear layer near the nozzle exit grow as they propagate downstream and interact with shock cells in the jet plume. This interaction generates strong acoustic waves that travel upstream and in turn interact with the shear layer and nozzle lip, thus exciting further instabilities. Supersonic jet screech has been extensively studied over the years (see reviews in Refs. [11, 12]) and is still a topic of active research, in particular in terms of the upstream-traveling component of the feedback loop [13, 14]. While the screech frequencies can generally be well estimated based on phase criteria for the closed feedback loop, the screech amplitude is less well understood and remains challenging to predict. Here, the reduced computational cost of the GPU-accelerated solver provided an opportunity to start exploring some of the sensitivities of the screech amplitude to nozzle design features.

### II. Overview of jet configuration and numerical approach

#### A. Experimental setup

The experimental setup has been designed and fabricated at the Gas Dynamics and Turbulence Laboratory at OSU to study flow physics, aeroacoustics, and active flow control of closely-spaced supersonic twin rectangular jets. The setup is briefly summarized here and more details of the facility, experimental configuration and
measurements can be found in Esfahani et al. [8] and Leahy et al. [9]. As shown in Figure 1, each rectangular nozzle is a bi-conical nozzle with a sharp throat and design Mach number \( M_d = 1.5 \), height \( h = 12.065 \) mm and aspect ratio width-to-height \( w/h = 2 \). The area-based equivalent nozzle diameter \( D_e \) is defined as the diameter of a circular jet whose exit area is the same as the rectangular cross-section. The value is \( D_e = 19.25 \) mm, or \( D_e/h = 1.6 \), which is also the twin jet spacing, i.e., the inner distance between the nozzle sidewalls at the exit. The center-to-center spacing between the nozzles is therefore \( 2.25D_e \).

Figure 2 shows the installation of the twin nozzles in the wind-tunnel facility. Several experimental campaigns have been conducted at OSU, in particular acoustic measurements in the near-nozzle exit and near-field region to study jet coupling & growth/decay of wavepackets/instability waves, and in the far-field to investigate radiated noise. Figure 3 shows schematics of the different microphone arrays. For the current configuration, the cabling required for the plasma actuation is present in all the baseline measurements and all the upstream reflective surfaces (including the pipe) have been covered with thick open cell acoustic foam. Experimentally, it was found that covering the co-flow channel tip had a significant effect on screech amplitude. Similarly, Leahy et al. [9] reported that the screech feedback loop and amplitude can be affected by ambient temperature and moisture levels as well as any variations in jet stagnation temperature. These sensitivities further highlight the challenges of accurately predicting screech amplitude.

### B. Large-eddy simulation methodology

The computations are performed using the LES framework and unstructured compressible flow solver “charLES” developed at Cascade Technologies. The mesh is generated through the computation of Voronoi diagrams: Cascade’s Voronoi-based meshing technology computes a grid from the specification of the relevant surface geometry and the set of generating points where the solution is to be sampled. For this complex rectangular nozzle configuration, the approach drastically simplifies the meshing process and the generation of a high-quality mesh well-suited for large-eddy simulations does not present any particular challenge, even with the inclusion in the computational domain of all the groove, electrodes and small geometrical details inside the nozzle, which are expected to be important for the flow physics and plasma modeling. For the present version of the charLES software, the flow solver is GPU-accelerated, with multi-GPU capabilities on both NVIDIA and AMD hardware. A mixed precision implementation was used to increase solver throughput without adversely affecting the accuracy of the acoustic predictions.

In this study, the simulations correspond to the baseline conditions without plasma actuation. The numerical setup is described in more details in Ref. [7] and is only briefly summarized here for completeness. The LES nondimensionalization is based on the nozzle height \( h \) and the ambient speed of sound \( c_\infty = \sqrt{\gamma p_\infty / \rho_\infty} \). The resulting form of the ideal gas law is \( p = \rho T / \gamma \), with constant specific heat ratio \( \gamma = 1.4 \). The nozzle pressure ratio and nozzle temperature ratio are defined as \( NPR = p_t / p_\infty = 3.67 \) and \( NTR = T_t / T_\infty = 1 \), where the subscript \( t \) and \( \infty \) refer to the stagnation (total) property and free-stream conditions, respectively. For the present nominally ideally-expanded conditions, the jet is cold (\( T_j / T_\infty = 0.69 \)) and the jet Mach number and acoustic Mach number are defined as \( M_j = U_j / c_j = M_d = 1.5 \) and \( M_a = U_j / c_\infty = 1.25 \), respectively.
where $U_j$ is the mean (time-averaged) streamwise jet velocity and the subscript $j$ refer to the (equivalent) fully-expanded jet properties. The experimental Reynolds number is $Re_j = \rho_j U_j D_e/\mu_j \approx 10^6$ and is matched in the simulations. In the wind-tunnel, the twin-jet nozzle assembly is installed inside a co-flow channel which is not active for this configuration and not included in the computational domain (see figure 4). The midpoint between the nozzle spacing is at $(x, y, z) = (0, 0, 0)$, such that the two nozzle exits are centered at $(0, 0, \pm 1.8h)$.

The rest of the numerical setup is similar to previous jet studies with the (CPU-based) charLES solver [15, 16, 17, 18]. A very slow coflow at Mach number $M_\infty = 0.01$ is imposed outside the nozzle in the simulation, to prevent any spurious recirculation and facilitate flow entrainment. Sponge layers and damping functions are applied to avoid spurious reflections at the boundary of the computational domain [19, 20]. The Vreman [21] 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 [22] of the Ffowcs Williams & Hawkings [23] (FW-H) equations. For the treatment of the FW-H outflow disk, the method of “end-caps” of Shur et al. [24] is used. To try to capture the thin internal boundary layer and nozzle-exit turbulent state [16], wall-stress modeling based on the equilibrium boundary layer assumption [25, 26, 27] and near-wall grid refinement are used for the interior surface of the nozzle, in the convergent duct and divergent sections (see figure 4(c)). The other solid surfaces are treated as adiabatic no-slip walls. Table 1 summarizes the operation conditions, along with details of the computations. For noise predictions, the FW-H surface data is sampled every 50 time steps (i.e., $DSt = 10.24$)

<table>
<thead>
<tr>
<th>NPR</th>
<th>NTR</th>
<th>$M_j$</th>
<th>$M_\infty$</th>
<th>$T_j/T_\infty$</th>
<th>$Re_j$</th>
<th>$dtc_\infty/h$</th>
<th>$t_{sim}c_\infty/h$</th>
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<td>3.67</td>
<td>1.0</td>
<td>1.5</td>
<td>1.25</td>
<td>0.69</td>
<td>1E6</td>
<td>0.0025</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 1. Summary of operating conditions and computational parameters, including simulation time step $dt$ and total simulation time $t_{sim}$ for the collection of data and statistics.

Figure 3. Description of the experimental microphones (from Refs. [8] and [9]).
C. Acoustics postprocessing

All the noise results are reported in terms of power spectral density (PSD, in dB/St) as a function of frequency in Strouhal $St = fD_e/U_j$ and overall sound pressure levels (OASPL, in dB), relative to $p_{ref} = 20 \times 10^{-6}$ Pa. All the FW-H calculations are performed at the exact location of the experimental microphones, assuming lossless propagation. For the far-field microphones, the effects of atmospheric absorption [28] is then included in the FW-H results for comparison with the as-measured data, using the ambient temperature and relative humidity in the wind-tunnel the day of the measurements. For the microphone locations and relatively high frequencies considered in this scale model configuration (i.e., the distance of propagation is $O(3)$ m and $St = 3$ corresponds to approximately 66 kHz), the atmospheric absorption is not negligible and leads to a reduction to $1.2 - 3.3$ dB in the $St = 1 - 3$ frequency range.

For reference, the experimental time-history of pressure data is recorded as 100 blocks of 32,768 samples for the near-field microphones and 400 blocks of 8,192 samples for the far-field microphones, with sampling frequency $Df_{exp} = 200$ kHz (i.e., $DSt_{exp} = 8.9$). The samples within a block are time-resolved, but not time-resolved between blocks. The duration of each experimental block is $t_{exp}/h \approx 4522$ and 1131 acoustic time units, for the near-field and far-field microphones respectively, compared to the simulation data for a single block of 2000 acoustic time units in the LES. For each block, the narrowband PSD is computed, and for the experimental data, average and rms values over all the blocks are then calculated. The rms can be useful as a measure of the block-to-block variation in the short-time-averaged spectra of the long experimental measurements, to reflect on the differences in statistical averaging between the experiment and the LES.

For both the experimental and numerical data, a (raw) bin-average PSD is computed from the narrowband PSD, with a relatively small bin size $\Delta St = 0.01$ to properly represent the screech tones. Following the procedure by Leahy et al. [9], a smoothed (de-toned) PSD is also computed by applying a moving median filter to the narrowband PSD with a window size of 1000 Hz. This filter removes sharp peaks associated with the jet screech and highlights the broadband characteristics of the noise spectra without the uncertainties associated with the screech tone amplitudes. The raw and de-toned OASPL are then calculated by integrating the corresponding PSD over the specified frequency range.

D. Previous work & present numerical setup

In previous work [7], a single initial (CPU-based) LES was performed at the baseline conditions (i.e., no plasma actuation) without prior knowledge of the experimental data. The mesh used for the initial simulation contained approximately 65 million cv, with emphasized refinement along the walls and within the shear layer of the jet. The finest resolution was $\Delta = 0.01h$ in the near wall region, including the plasma groove, such that there were approximately 8 cv and 4cv in the width and depth of the groove, respectively. After the initial transient, the runtime for collection of statistics was $t_{sim}/h = 611$ and the computational cost was approximately 240 kCPUh (i.e., time-to-solution of 36h on 6600 cores). Overall, the preliminary noise predictions were in good agreement with the microphone data for most relevant frequencies and angles.

To investigate some of the small discrepancies observed in the comparisons with the initial LES, additional simulations are performed in the present work with the GPU-accelerated solver. The key differences between
the two sets of computation can be summarized as follows. First, additional grid refinement is applied in
the near-wall region inside the nozzle and in the jet plume to further improve noise predictions at higher
frequencies. The finest resolution in the near-wall region is now $\Delta = 0.005h$, effectively doubling the number
of cells across the width and depth of the groove. As shown in figure 5, the resolution is $\Delta = 0.01h$ to $0.02h$
in the near-nozzle exit region (up to $x = 8h$) and then increased to $\Delta = 0.04h$ in the bulk of jet plume up
to $32h$ downstream of the nozzle. The total mesh size is increased to approximately 97 million cv.

Second, the simulation runtime for collection of statistics (after the initial transient removed) is increased
to $t_{\text{sim}} c_\infty / h = 2000$ acoustic time units. The present single time block of LES data is therefore the same
order of magnitude in duration than a block of experimental data.

Third, the installed configuration in the OSU wind-tunnel facility includes thick open cell acoustic foam
and cabling on the supply pipe surfaces upstream of the nozzle exit (see figure 2(c)) which are challenging to
model in the LES and can be expected to have an impact on the feedback loop and screech tone amplitude.
To investigate these effects, a second “non-reflective” nozzle is considered in which all the reflective surfaces
associated with the supply pipe are removed. Figure 6 shows a comparison of the original and non-reflective
nozzles. The changes were done in Cascade’s pre-processing tool without the need of a CAD package. Aside

Figure 5. Description of the grid refinement up to $45h$ downstream of the nozzle exit. The gray scale contours
represent mesh resolution levels from $\Delta = 0.005h$ (light) to $0.32h$ (dark).

Figure 6. Overview (left) and top view (right) of the two nozzle configurations considered in the simulations.
from the removal of the supply pipe, all the details of the twin nozzles are retained in the computational domain, including the external shape and the internal groove and electrodes. The total mesh size is slightly reduced to 94 million cv. The operating conditions, numerical setup, mesh resolution and runtime are kept identical for the two independent simulations with original and non-reflective nozzle (see table 1).

Finally, the present simulations are performed with the GPU-accelerated version of the charLES flow solver. The computational cost for the collection of 2000 acoustics time unit of data on the 97 million cv mesh was approximately 360 GPU hours (i.e., time-to-solution of 12h on 30 GPUs). Thanks to the GPU acceleration, the time-to-solution was therefore cut down by a factor of 3 compared to the previous initial (CPU-based) LES, even though the mesh size was increased by about 50% and simulation runtime was more than tripled. Additional details about the GPU-accelerated solver performance and scalability are presented in section IV.

III. Results and analysis

A. Flow field

As a qualitative visualization of the jet flow, numerical schlieren of the instantaneous density are shown in figure 7 in planar cuts through the centerlines long the major and minor axis. Surface pressure fluctuations are also visualized on the original nozzle geometry. Since the configuration features bi-conical nozzles with sharp throat, there are shock cells in the potential cores even for the present nominally ideally-expanded conditions. As discussed in more detail in the next section, the imprints of upstream-traveling acoustics waves are visible on the nozzle external surfaces upstream of the nozzle exit, which can have an impact on aircraft structural fatigue.

Figure 7. Visualization of the pressure fluctuations \((-0.01 \leq (p - p_{\infty})/p_{\infty} \leq 0.01)\) on the twin rectangular nozzle external surfaces and numerical schlieren \((0.75 \leq \exp(-5|\nabla \rho|/\max(|\nabla \rho|) \leq 0.99)\) in the jet plume for the original nozzle.
Figure 8 shows the instantaneous pressure fluctuation \( \frac{p - p_\infty}{p_\infty} \) in the same planar cuts for the full computational domain. The effects of the sponge layers applied away from the nozzle and jet plume can clearly be seen in the figure as acoustics waves are damped towards the boundary of the domain without spurious reflections. Aside from the typical broadband noise radiation pattern toward the aft angles (i.e., polar angles \( \theta \approx 30 - 55^\circ \)) associated with the Mach waves, the main features in the pressure field are the strong upstream-traveling acoustic waves from the jet screech feedback loop. The waves have a well-defined wavelength \( \lambda/h \approx 4.27 \) related to the main screech frequency at \( St \approx 0.3 \) and are more intense along minor axis for both nozzles (see images on the right in figure 8). With the original nozzle, there is an additional downstream radiation pattern near the nozzle exit associated with the reflections of the waves off the supply pipe surfaces. These reflected waves are not present for the non-reflective nozzle with the supply pipe removed.

(a) Original nozzle

(b) Non-reflective nozzle

Figure 8. Planar cuts of the instantaneous pressure (left) in the \( y = 0 \) plane (i.e., through centerline along major axis) and (right) in the \( z = 1.86 \) plane (i.e., through centerline along minor axis) for the original and non-reflective nozzles: \( \frac{p - p_\infty}{p_\infty} \) from \(-0.01\) (black) to \(0.01\) (white). The solid nozzle surfaces are shown in golden color.
B. Near-field noise

More quantitative noise results are presented in this section for the nozzle-exit microphone array and the linear microphone array described in figure 3(a) and (c), respectively. As discussed in Refs. [8, 9], the nozzle-exit microphone array was designed specifically to provide information on screech frequency and on twin jets coupling modes. Similarly, the linear microphone array was setup specifically to investigate growth and decay of large-scale wavepackets/instability waves along the jet plume and its location in the $z = 0$ plane between the two nozzle was chosen to minimize the effects of probes on the screech and coupling. For these near-field measurements, a protection grid cap is used to protect the microphone from getting damaged, and the acoustics at higher frequencies is challenging to capture. Therefore, the near-field spectra comparisons are limited to frequencies up to $St \approx 1 - 1.5$. Both raw and de-toned OASPL are computed through integration of the corresponding PSD over $0.04 \leq St \leq 1.5$.

![Graphs showing noise comparisons at the nozzle-exit microphone array](image)

Figure 9. Noise comparisons at the nozzle-exit microphone array (see figure 3(a)) between the experimental measurements (—— •) and the GPU-accelerated LES predictions for the original nozzle (—— △) & non-reflective nozzle (—— □). The vertical bars show the block-to-block variations in the short-time-averaged spectra of the long experimental data, compared to the 1-block LES data. The dashed line corresponds to the theoretical decay of pressure fluctuations in isotropic turbulence with $-7/3$ slope.
Experimental measurements and numerical predictions of the near-field noise are presented in figure 9 for the nozzle-exit microphone array. Given the nozzle symmetries, similar results can be expected for the statistically-equivalent microphones 1 & 4 along the major axis, and 2, 3, 5 & 6 along the minor axis (see photograph of nozzle-exit microphone locations in figure 3(a)). Overall, the agreement is good over most of the frequency range and the main screech tone frequency at \( St \approx 0.3 \) is well predicted. The jet screech is more intense along the minor axis (i.e., mic 2, 3, 5 & 6) than along the major axis (i.e., mic 1 & 4), consistency with the visualization of the pressure fluctuations in figure 8. For \( St < 0.25 \), the lobes in the low-frequency spectra are well captured for the simulation with the original nozzle and the agreement gets slightly worse with the non-reflective nozzle. Here, the large supply pipe geometry upstream for the nozzle exit seems to play a key role in setting up the acoustic waves with long wavelengths. The main difference between the two LES predictions is the screech tone amplitude: for the original nozzle, the amplitude along the minor axis is over-predicted by \( 3 - 5 \) dB. With the non-reflective nozzle, the screech amplitude now is within \( 1 - 2 \) dB for most microphones. Similarly, some of the additional lobes around \( St \approx 0.42 \) and 0.55 have been reduced for the non-reflective nozzle for a closer match with the experimental spectra.

These differences in screech amplitude can clearly be seen in the comparisons of the raw and de-toned OASPL in figures 9(g) & (h). For the raw OASPL with all the tones included, the LES results for the non-reflective nozzle (i.e., upstream supply pipe reflective surfaces removed) match the experimental results (i.e., surfaces covered by acoustic foam) within \( 0.5 - 1 \) dB while the original nozzle produces higher raw OASPL levels because of the stronger screech tone along the minor axis. For the de-toned OASPL with the screech contributions removed, all levels are reduced and now similar in magnitude.

Similar conclusions holds for the near-field noise shown in figure 10 at the linear microphone array. Again, with the original nozzle, the low-frequency lobes are remarkably captured, in particular at the microphones 5 & 6 closer to the nozzle exit, but the amplitude of the screech primary tone at \( St \approx 0.3 \) is over-predicted. With the non-reflective nozzle, the amplitude is reduced and the simulation recovers the experimental trend that the screech tone first harmonic at \( St \approx 0.6 \) is the main feature in the near-field spectra in the \( x/D_e = 4-8 \) region (i.e., microphones 8 to 11). For \( St > 1 \), some small discrepancies are observed because of the challenges of the high-frequency measurements previously discussed. The LES spectra are similar for both nozzles, with a more uniform \(-7/3\) slope corresponding to the traditional decay rate of pressure fluctuation in isotropic turbulence. Inspection of the raw and de-toned OASPL in figures 10(g) & (h) confirms that most of the discrepancies are due to the differences in screech amplitude predictions. To quantify growth and decay of large-scale wavepackets/instability waves, the de-toned levels are more relevant and the predictions matches the measurements within \( 0.5 - 1 \) dB for most microphones.

### C. Far-field noise

Finally, the far-field noise comparisons are shown in figure 11. For theses microphones, the protection grid cap is not used: the spectra comparisons are reported up to \( St = 3 \) and the raw OASPL is computed through integration of the PSD over \( 0.04 \leq St \leq 3 \). Further inspection of the experimental setup pointed out that part of the field of views for the normal and upstream microphones in figure 3(b) could be affected by the thick nozzle lip design to accommodate the plasma actuators. Based on these discussions with the experimentalists at OSU, the comparisons are presented up polar angle \( \theta = 75^\circ \).

Overall, the agreement is good for all the microphones over the full frequency range. For most relevant angles and frequencies, the LES predictions are within the small block-to-block variations of the experimental data (i.e., vertical bars in figure 11), of order \( \pm 0.5 \) to \( 1.5 \) dB. In the far-field, the dominant component of the radiated noise is the broadband mixing noise towards the aft angles (i.e., \( \theta \approx 30 - 50^\circ \)) associated with the large-scale wavepackets/instability waves, rather than the tonal screech noise. The de-toned OASPL is therefore nearly identical to the raw OASPL, and is not reported. The simulations for both original and non-reflective nozzle also show similar results in terms of far-field radiated noise. The only difference is that the screech primary tone at \( St \approx 0.3 \) is visible in the spectra along the minor axis for the original nozzle and not for the non-reflective nozzle & experiment. This is likely related to the enhanced contributions from reflected waves bouncing off the upstream supply pipe surface and propagating towards the aft angles, as shown in the instantaneous field of pressure fluctuations in figure 8(a) for the original nozzle. However, these contributions are small and the OASPL directivity is well captured for both simulations: the predicted OASPL levels are again within \( 0.5 - 1 \) dB of the experimental measurements.
Figure 10. Noise comparisons at the near-field linear microphone array (see figure 3(c)) between the experimental measurements (●) and the GPU-accelerated LES predictions for the original nozzle (△) & non-reflective nozzle (□). The vertical bars show the block-to-block variations in the short-time-averaged spectra of the long experimental data, compared to the 1-block LES data. The dashed line corresponds to the theoretical decay of pressure fluctuations in isotropic turbulence with $-7/3$ slope.
Figure 11. Noise comparisons at the far-field microphone array (see figure 3(b)) between the experimental measurements (---•) and the GPU-accelerated LES predictions for the original nozzle (---△) & non-reflective nozzle (---□). The vertical bars show the block-to-block variations in the short-time-averaged spectra of the long experimental data, compared to the 1-block LES data. The dashed line corresponds to the theoretical decay of pressure fluctuations in isotropic turbulence with $-7/3$ slope.
IV. Scalability study of the GPU-accelerated solver

As mentioned in section IID, the present simulations were performed on 30 GPUs, corresponding to 15 MLA-2 accelerated nodes of the HPE Cray EX system “Narwhal” located at the US Navy DoD Supercomputing Resource Center (DSRC). Each node has 2 NVIDIA V100 PCIe GPUs with 32GB of memory per GPU and HPE Slingshot interconnect.

For the 97 million cv mesh, a strong scalability study was also conducted on the Narwhal system, from 5 to 30 nodes (i.e., nearly the full set of available GPUs). Figure 12 shows the solver speedup compared to ideal speedup, as well as the loading (in Mcv per GPUs) as a function of the GPU count. The GPU-accelerated solver scales perfectly up to 30 GPUs, corresponding to a loading of approximately 3.2M cv per GPU, and remains at about 90% scalability on 60 GPUs, for a loading as low as 1.6M cv per GPU.

For comparison, the performance of the CPU-based version of the solver was tested for the same jet case on Narwhal standard HPC nodes, with 128 AMD 7H12 Rome processors per nodes. Here, each V100 GPU is found to be equivalent in throughput to $O(400)$ cores, which is similar to the equivalence observed for the ideal-gas compressible flow solver on other HPC systems. This acceleration enables simulation turn-around times of order hours on just 10s of GPUs for mesh sizes relevant to practical engineering applications.

V. Conclusions

Large eddy simulations are performed for Mach 1.5 jets issuing from a twin rectangular nozzle of aspect ratio 2, using the GPU-accelerated version of Cascade’s compressible flow solver “charLES”. The operating condition and complex nozzle geometry match the experimental configuration from Ohio State University, which was designed to investigate the effects of plasma actuation[8, 9]. In this initial study, the LES are conducted at the baseline conditions (i.e., no plasma actuation) but all the nozzle internal details are included in the computational domain, i.e., the electrodes and small groove upstream of the nozzle exit to shelter the arc discharge between electrodes during actuation.

Comparisons of the experimental measurements and LES predictions at near-field and far-field microphones show good overall agreement in terms of screech tone frequencies, broadband levels, and main far-field noise radiation towards the aft angles. In contrast, the screech feedback loop and tone amplitudes are more sensitive to the precise operating conditions & nozzle geometrical details, and therefore more challenging to measure and predict. To account for the thick open cell acoustic foam installed in the wind-tunnel on the supply pipe surfaces upstream of the nozzle exit, a second “non-reflective” nozzle was simulated in which all the reflective surfaces associated with the supply pipe are removed. For the original nozzle with the reflective surfaces included, the screech tone amplitude at the near-field microphones along the minor axis is over-predicted by 3 – 5dB. With the non-reflective nozzle, the screech amplitude is reduced and within 1 – 2 dB of the measurements for most microphones.
In terms of performance with the GPU-accelerated solver, the computational cost for the collection of the relatively long noise database of 2000 acoustics time unit on the 97 million cv mesh was approximately 360 GPU hours. This represents a time-to-solution of 12h on 30 Nvidia V100 GPUs. For this case, a strong scalability study was also conducted on “Narwhal” (HPE Cray EX system) at Navy DSRC. The GPU-accelerated version of charLES displayed 90% scalability on 60 GPUs (i.e., loading of 1.6M cv per GPU), with a throughput of $O(400)$ equivalent cores per V100 GPU. This reduction in computational cost will make possible the exploration of more nozzle designs and/or actuation cases in future work, along with the collection of longer LES databases for statistical (SPOD) analysis[29].

Acknowledgments

The LES studies are supported in part by NAVAIR award N68335-21-C-0270 and by ONR award N00014-20-1-2311 in collaboration with Prof. Tim Colonius (Caltech) Prof. Oliver Schmidt (USCD), under the supervision of Dr. Russell Powers and Dr. Steve Martens, respectively. Support from the US Department of Energy award DE-SC0020548 is also acknowledged. The LES calculations were carried out on “Narwhal” (HPE Cray EX system) at Navy DSRC, with additional testing on “Onyx” (Cray XC40/50 system) at ERDC DSRC, using allocations provided by DoD HPCMP. The authors would like to thanks Prof. Mo Samimy, Ata Esfahani, Nathan Webb and Ryan Leahy (OSU) for the nozzle geometry, the experimental measurements, and the many insightful discussions.

References


