Massively-Parallel Simulations of Supersonic Jet Noise from Complex Nozzles

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August 7, 2013

Importance and challenges of jet noise predictions for tactical aircraft

The operation of modern tactical aircraft, in particular from aircraft carrier decks, exposes military personnel to extreme noise environments that can result in significant and permanent hearing loss. Unlike commercial airplanes, the propulsion systems of combat aircraft are based on low bypass ratio turbo-jet engines. The exhaust jets are supersonic and hot, especially with the augmenter/afterburner in operation. In some cases, this can lead to crackle, which is an especially irritating component of supersonic jet noise because it is associated which N-shaped acoustic waveforms with sudden strong compressions followed by more gradual expansion. In addition, the static pressure at the exit of the nozzle is generally not matched with the ambient pressure during high-powered take-offs and landings. The pressure mismatch generates a shock-cell system in the jet exhaust plume that interacts with the jet turbulence. These interactions generate additional jet noise components, namely broadband shock-associated noise (BBSN) and tonal screech noise.

It has been estimated that, in the US military, the disability claims associated with hearing loss exceed $1B each year. Finding effective strategies to mitigate the exposure to the severe noise without severely impacting propulsive performance are therefore critical. Until recently, the development of such strategies has relied largely on laboratory and full-scale testing, as well as some numerical prediction tools typically based on empirical databases, modeling and Reynolds–Averaged Navier–Stokes (RANS) approaches. However, cost constraints and the high complexity of the flow often limit the range of the parametric investigation and the success of the design optimization. Likewise, while semi-empirical numerical methods provide useful first estimates, they tend to lack the sensitivity to design/configuration changes needed in a design tool, and are largely untested for complex settings such as multi-stream nozzle or carrier-deck takeoff conditions.

In this context, high-fidelity unstructured large eddy simulation (LES) is emerging as an accurate yet cost-effective computational tool for prediction of turbulent jets and their acoustic fields, for multiple reasons. First, it is a fully predictive approach based on first principles, free of user-defined calibration or empirical constants. Second, the complex nozzle geometries, such as chevrons, faceted military-style nozzle and multi-stream architecture, can be explicitly included in the simulations thanks to the unstructured mesh capabilities, enabling the direct study of the variation of flow and emitted noise by different nozzle configurations. Third, LES provides access to the complete transient flow field, allowing in-depth probing of the physics of jet noise production. Finally, advancement in high-performance computing (HPC) has enabled large-scale high-fidelity LES to become a practical engineering solution for design studies. Access to current (and future) supercomputer facilities has brought forward a new engineering paradigm for massively-parallel methods. This contrasts with past school of thought and existing approaches, which rely on low-cost methods, modeling and empirical databases.

The last point is particularly relevant for the DoD High Performance Computing Modernization Program. As previously mentioned, the RANS approach is currently an industry standard in CFD for aerospace applications, but significant modeling and calibration are required to account for flow turbulence and to ultimately predict noise. The other important limitation of the RANS approach for future design studies is the absence of a path to higher accuracy with increasing computer power. That is, the predictive accuracy of the RANS method is not necessarily improved by increasing the spatial and temporal resolution of the computational grid; it is limited by the (irreducible) errors of the turbulence closure models. In contrast, LES has a well-defined path to increased predictive capability through increased computer power. Through increased spatial and temporal resolution, afforded by advances in computer technology, the LES equations approach the true flow equations derived from first principles as the effect of phenomenological subgrid scale models diminish. The current industry standard engineering design tools have plateaued in their ability to harvest increasing computer power and to resolve the critical technical challenges that arise as the complexity of the nozzle geometry and operating conditions is increased. The next generation of predictions tools for engineering design of future tactical aircrafts nozzles should be developed with first-principles approaches, such as LES, and anticipate the continued advancements in high-performance computing.

"Charles": The high-fidelity massivelly-parallel compressible flow solver

Through several projects funded by NASA, Air Force, NavAir and the office of Naval Research (ONR), and in collaboration with Stanford University, there has been a significant and continuous effort over the past few years to improve understanding and develop predictive capabilities of propulsive jet aeroacoustics, through high-fidelity physics-based simulations with the unstructured LES framework developed at Cascade Technologies. For aeroacoustics, the framework is composed of pre-processing tools (e.g., for unstructured mesh refinement and adaptation capabilities, see next section), a compressible flow solver Charles, and post-processing tools (e.g., for far-field noise prediction). The solver Charles features all the capabilities required to efficiently perform large-scale high-fidelity aeroacoustics simulations of turbulent jet flows from complex geometries (i.e., unstructured grid capabilities, low-dissipative numerical schemes, shock capturing scheme, subgrid scale modeling, high parallel computing performances, etc.). For the far-field noise predictions, an efficient frequency-domain permeable formulation[1] of the Ffowcs Williams–Hawkings (FW-H) equation[2] has been implemented in Cascade's massively-parallel unstructured LES framework[3]. As an example of the typical LES setup for aeroacoustics, figure 1 shows the computational domain for a hot supersonic jet issued from a rectangular nozzle[4], including the FW-H surface used to propagate the near-field LES data to the far-field and compute the radiated noise. The instantaneous temperature and pressure fields are also shown, to visualize the shock cells, screech noise and broadband jet noise.

One of the unique features of Charles is the solver performance and scalability on massively-parallel environments. The solver is designed and implemented using Message Passing Interface (MPI) to function well in a massively parallel, distributed memory environment. Calculations are carried out routinely on several thousand of processors at DoD supercomputer facilities in ERDC and AFRL. Scalability studies performed during the Cray XE6 testing period of 2010 (CAP and CAP-2 early access programs) demonstrated

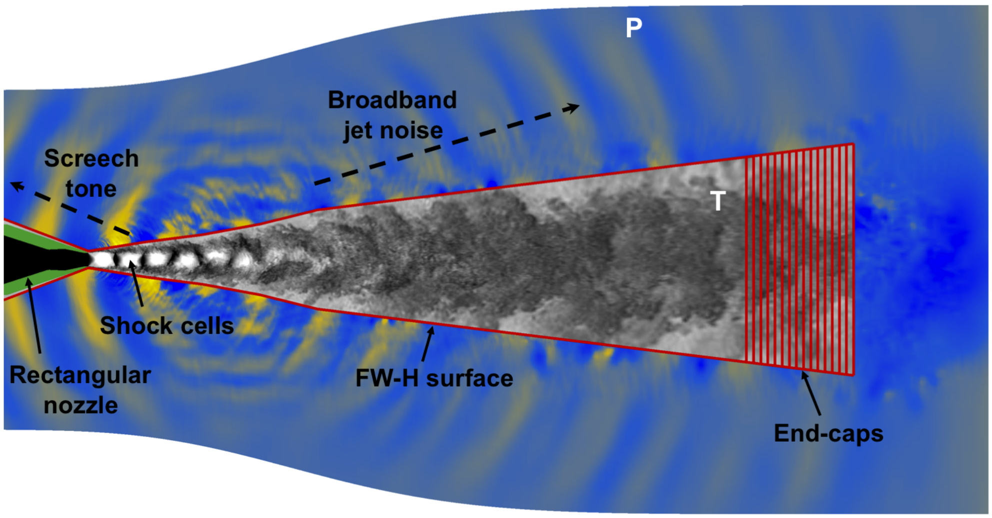


Figure 1: Typical LES setup for aeroacoutics: example of a hot supersonic jet issued from a rectangular nozzle[4]. Inside the FW-H surface, the shock cells and turbulence of the supersonic jet flow are visualized by grayscale contours of temperature T, with black and white corresponding to hot and cold, respectively. The direct near-field sound outside of the FW-H surface is displayed by color contours of pressure P.

that the code exhibits perfect scaling at the 20,000 core level. The algorithm efficiency, defined as the speed-up divided by the number of participating processors, remains at 97% for 20,000 cores compared to 100% at the 2,048 core baseline.More recent scalability tests on different systems showed that the code exhibits good scaling for up to 160,000 cores. Figure 2 shows scaling statistics (speed-up vs. number of cores) for a jet noise simulation[5] on a mesh with 528M control volume, computed on the Intrepid system at Argonne National Labs (ANL). The calculation on 163,840 cores used the full capabilities of the system, at 80% parallel efficiency. Testing on these different systems (IBM BlueGene P & Q, CRAY XE6, SGI, commodity Linux clusters, etc.) also demonstrated great cross-platform portability.

Moreover, the Charles solver was recently run on over 1 million cores, reaching a new milestone in high performance computing. This breakthrough was realized in January 2013 during Early Science testing of the newly installed Sequoia supercomputer at Lawrence Livermore National Laboratory (LLNL), in collaboration with Stanford University and LLNL computing staff. The jet noise calculation performed during that breakthrough challenged all parts of these supercomputers because waves propagating throughout the tightly-coupled simulation required a well-orchestrated balance between computation, memory, communication, and I/O. The data from this simulation is being used to understand how such jets emit crackle noise, a significant and especially irritating part of the overall acoustic field (see section below).

From simple jet geometries to chevrons and military-style faceted nozzles

In past studies, Charles has been used to investigate a wide range of high-speed high Reynolds number unsteady flow processes for various jet configurations, including impinging flows[6, 7], circular[8, 9, 3] and rectangular[4, 10] jets, chevrons[11, 5], faceted military-style nozzle[12, 13], and internally-mixed dual-stream jet[14]. Access to DoD supercomputers and "Challenge" status granted by the HPC programs were critical

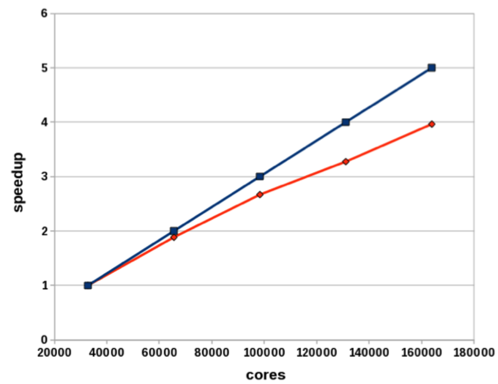


Figure 2: Scalability of the LES code Charles on the Intrepid system at Argonne National Labs (up to 163,840 cores)

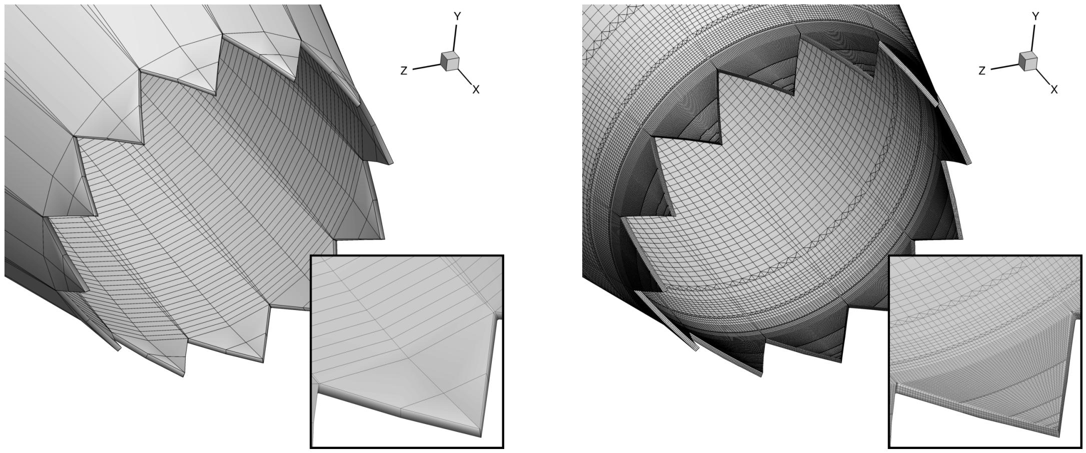
to the success of these research projects.

While the simulations have progressed from simple geometries to more complex configurations in recent work, all the studies have in common that the complex nozzle is explicitly included in the computational domain using unstructured body-fitted mesh and adaptive grid refinement. Here, it is important to point out that the generation of a high quality mesh for a complex geometry remains a pacing issue in high-fidelity flow simulation. LES places strict requirements on mesh resolution, element quality, and even the level of allowed mesh anisotropy. To address these challenges, a massively-parallel tool has been developed in Cascade's solver infrastructure to gives the user detailed control over the local mesh resolution in their grid. This mesh adaptation module "Adapt" features localized adaptive refinement capabilities and produces high-quality yet economical unstructured grids suitable for capturing turbulence dynamics.

An example of the use of "Adapt" is shown in figure 3 for a 12-count chevron appended on a round converging-diverging nozzle. The starting point is a very coarse grid containing about 0.16 million control volumes. Several embedded zones of refinement can then be simply defined by the user and automatically enforced by the adaptation tool Adapt. The code includes a smoothing algorithm to avoid sharp grid transitions between different refinement zones. A surface projection method is also applied to respect non-planar mesh boundaries during refinement, ensuring accurate representation of the underlying geometry. The use of very coarse grids as starting point is a convenient approach, as it not only greatly simplifies the meshing process and reduces the burden on the users but also allows for complete control of the location and length scale of the refinement.

For this project, a grid resolution study was performed by increasing the mesh size from 55×10^6 to 118×10^6 and 386×10^6 cells, with the bulk of the mesh in the jet potential core and enclosing the FW-H surface. The grid refinement analysis showed that, while additional resolution is always beneficial to the numerical predictions, the grid size range of 50 to 60M cells seems to be a good compromise between accuracy and runtime/data storage for current computational resources. Figure 4 shows the flow field visualization for a heated supersonic over-expanded jet issued from the chevron nozzle presented in figure 3, on the 386M mesh. The development of fine turbulent structures from the chevrons nozzle exit to the end of the potential core, as well as the shock cell pattern, is clearly visible in the top figure. This example highlights some of the multi-physics capabilities of the solver as well as the low-dissipative aspect of the numerical scheme.

Figure 5 shows the noise spectra comparison between LES predictions and experimental measurements carried out at United Technologies Research Center (UTRC) for the same geometry and operating conditions. Both near and far-field noise predictions match the experimental results accurately over a wide range



(a) Initial coarse “skeleton” mesh (0.16M cells)

(b) Adapted mesh (55M cells)

Figure 3: Chevron nozzle surface mesh and zoomed-in view of chevron tip.

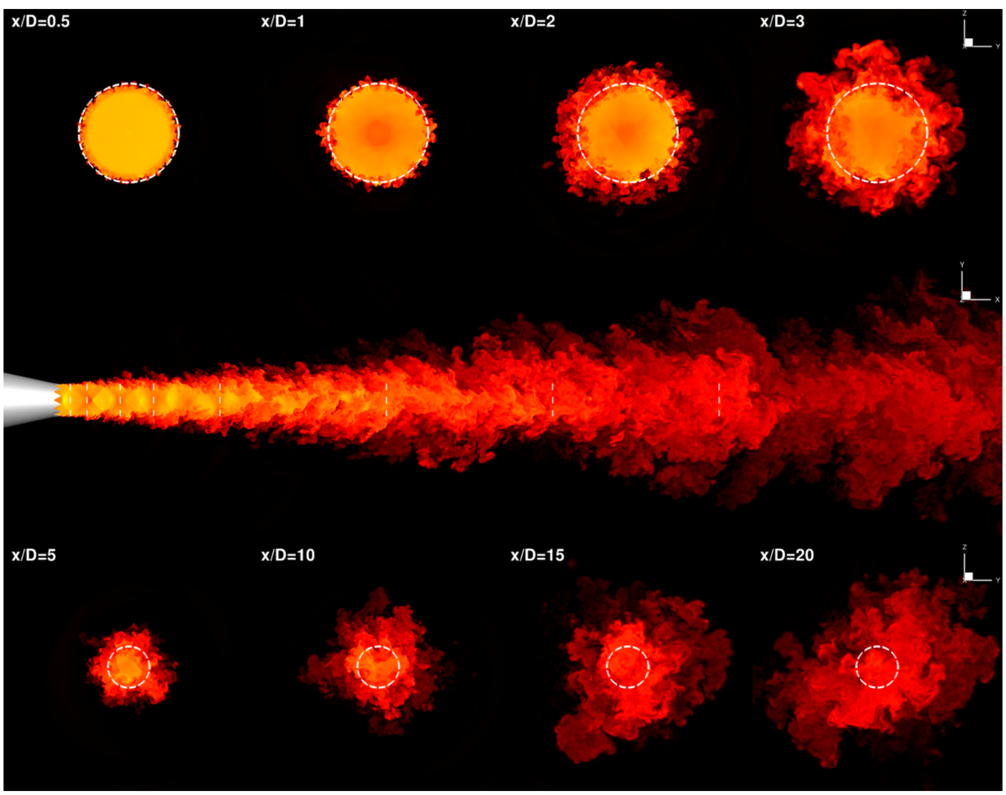
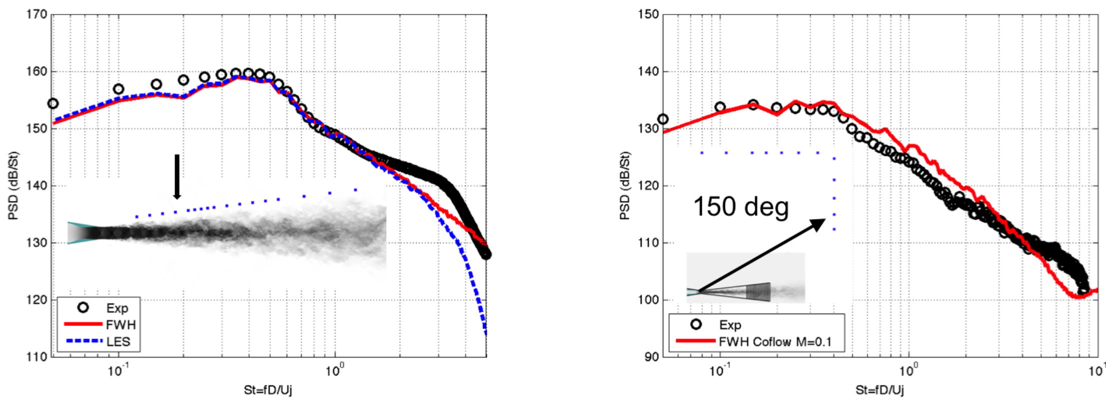


Figure 4: Instantaneous temperature field for a heated supersonic over-expanded jet issued from the chevron nozzle. The cross-flow cuts of the temperature at different locations downstream of the nozzle are shown in top and bottom subfigures. The dashed circular line corresponds to the nozzle exit outline.



(a) Near-field probe

(b) Far-field microphone

Figure 5: Blind comparison of the sound spectra at different locations between experimental (symbols) and LES (lines). See Ref. [11] for details.

of frequencies. It should be underscored that the results presented here correspond to blind comparisons, in the sense that all the simulations and postprocessing were performed without prior knowledge of the experimental data. This level of agreement is the state of the art in the field of computational aeroacoustics and demonstrates the fully predictive capabilities of the present high-fidelity LES. The large database generated during these studies are currently being used to evaluate chevron design, not only for noise reduction but also in terms of performance and thrust loss.

Crackle: the most annoying component of supersonic jet noise

While blind comparisons to aeroacoustic laboratory experiments have demonstrated the predictive power of LES, the potential of advanced simulation methods for scientific understanding is greater still. As mentioned above, LES provides access to complete three dimensional transient flow fields, in a fashion unparalleled by experimental measurements. In essence, LES functions as a computational microscope which scientists can use to understand the root causes of complex phenomena such as jet noise.

In this spirit of computation-based discovery, part of our research effort has been directed towards applying high-fidelity LES to understand the mystery of crackle noise that sometimes occurs in hot supersonic jets such as those produced by the exhausts of high-powered tactical aircraft. Crackle noise is characterized by N-shaped acoustic waveforms that result in intermittent sudden compressions in the pressure field at observer locations[15]. When crackle occurs, it is extremely irritating to human perception. Moreover, even though crackle is an intermittent phenomenon, it can account for a significant portion of the overall sound pressure level in the direction of the peak noise radiation[16]. Its elimination would therefore have the added benefit of decreasing the peak jet noise, an important factor for noise regulations ensuring safety of carrier deck personnel and maintaining community standards close to military bases.

Although mitigating crackle would have clear practical advantages, the fundamental mechanism by which it is produced has been the subject of recent debate. One possible explanation is that nonlinear effects cause acoustic waves of sufficiently high amplitude to steepen as they propagate, eventually leading to N-shaped waves interpreted as crackle. The propagation distance required for nonlinear effects to become significant, however, depends on the wave's initial amplitude, and in most cases is longer than distances

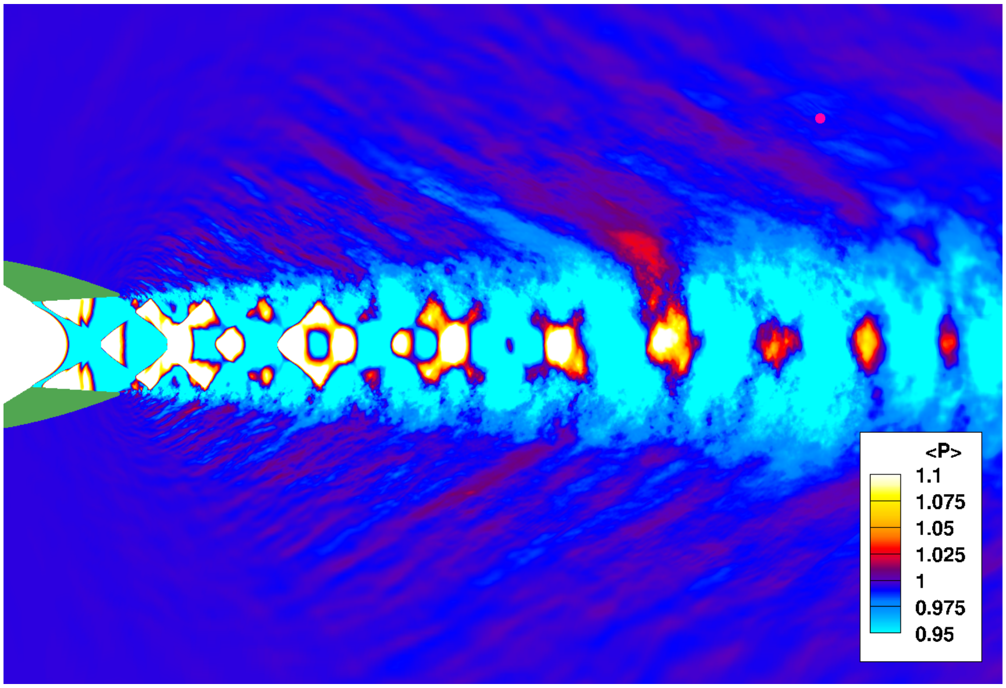


Figure 6: Contours of phase-averaged pressure on an axial cross section through a high-fidelity LES of a crackling supersonic jet.

relevant to an aircraft carrier deck[15]. Instead, our simulations have allowed us to observe N-shaped waves emerging directly from a spatially developing turbulent round supersonic jet issuing from a faceted military-style nozzle[12, 13]. An interesting aspect of our simulations is that once an N-shaped wave is detected at an observer location, the simulation, through checkpointing, is able to revert back to a precise earlier time, reconstructing the complete flow field responsible for producing that particular wave. Figure 6 shows an average of several such crackle-producing flow fields. Because time flows in one direction in the real world, such time-lagged phase-averaging is difficult to measure experimentally, except through the storage of tremendous amounts of data, which by necessity are of reduced spatial and temporal accuracy.

Figure 6 specifically shows color contours of the phase-averaged pressure on an axial cross section through a military-style nozzle (green, at left). The magenta circle in the upper right marks the observer location. In addition to the shock cells present in the core of the jet, a region of high pressure is observed to form on the upper edge of the jet, spanning the turbulent shear layer at that location. This suggests that crackle is generated by large-scale flow features embedded in the turbulence, and explains why recent full-scale tests involving military-style nozzles with chevrons (which tend to breakup large-scale flow features) have shown a reduction in crackle noise[17].

Conclusions and outlook

The paper is intended as an overview of the recent progress made with massively-parallel large eddy simulation for jet noise predictions of tactical aircraft. The compressible flow solver Charles used in the present jet noise studies is part of the multi-physics unstructured LES framework developed at Cascade Technologies,

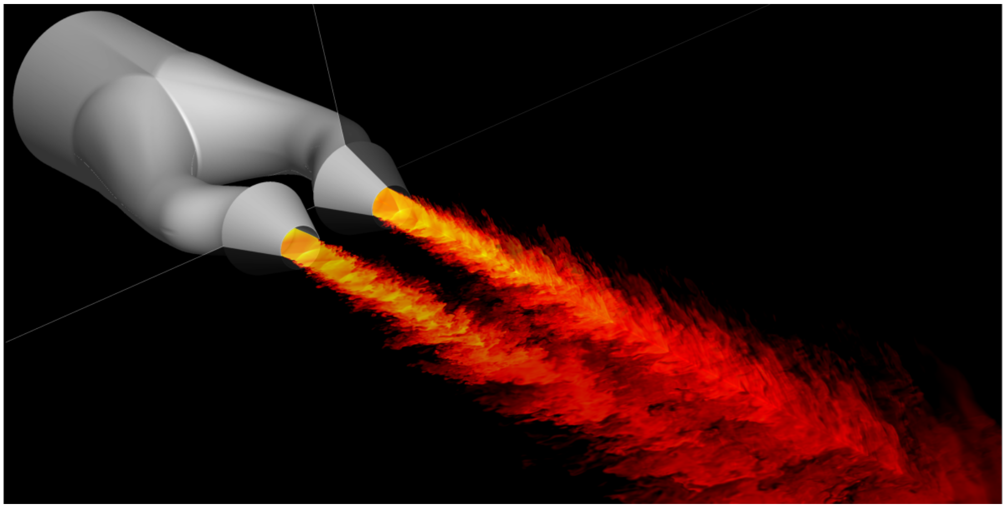


Figure 7: Temperature field for heated supersonic jets issued from a twin nozzle.

which extends to multi-phase and combustion applications. Over the past year, nearly 20 million computing hours from the DoD HPC Modernization Program were used to simulate heated supersonic jets and aero-engine injectors. These resources enabled us not only to investigate chevron effects on round nozzles and multi-phase flows in complex combustor/augmentor geometry, but also to explore other applications relevant to tactical aircraft, such as twin nozzle architecture (see figure 7) and crackle noise.

A continued effort is being made to conduct further analysis of the large LES database collected over the course of the current HPC Challenge Project. Experience gained from these studies is currently used for the mesh design, numerical setup and acoustic post-processing of ongoing work, to continue advancing existing methodologies towards best practices for jet noise predictions with unstructured LES.

Acknowledgments

The chevron nozzle study is supported by NavAir SBIR/STTR program, contracts N68335-11-C-0026 under the supervision of Dr. John T. Spyropoulos. The twin nozzle study is supported by ONR grant N00014-12-C-0010, under the supervision of Dr. Brenda Henderson. Most of the simulations were performed as part of the HPC Challenge Project "Large Eddy Simulations of Supersonic Jet Noise and Combustor & Augmentor Spray Atomization." The majority of calculations were carried out on "garnet", "raptor," and "spirit", at DoD supercomputer facilities in ERDC and AFRL.

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