WHITE **PAPER**

High-Fidelity Noise Prediction

For Aerospace and Automotive Industries

By Cadence

In the evolving aerospace and automotive industries, engineers face the complex challenge of high-fidelity noise prediction. Aeroacoustic simulations are vital for ensuring the comfort and satisfaction of passengers in transportation systems and reducing noise disturbances in urban settings. The following white paper summarizes the functionality and features of Cadence's high-fidelity computational fluid dynamics (CFD) software. This tool leverages large-eddy simulations (LES) to offer unprecedented accuracy in aeroacoustic simulations, providing a cost-effective and efficient alternative to traditional experimental methods. Through a detailed exploration of its state-of-the-art computational techniques and robust mesh generation strategies, this white paper emphasizes the solver's adaptability to modern high-performance computing (HPC) hardware. Its real-world applications also bear testimony to its potential as a pivotal tool in industrial settings.

Contents

Introduction

There's a growing demand for quieter and more efficient aircraft and automobiles in today's rapidly urbanizing world. As cities become more congested, the challenge of high-fidelity noise prediction becomes paramount, especially in enhancing the acoustic performance of transportation systems and reducing noise pollution. However, traditional experimental methods for studying aeroacoustics can be expensive and time-consuming. This is where aeroacoustic simulations are valuable for analyzing noise produced by aerodynamic forces in fluid flow, providing a better alternative to conventional methods.

A specialized simulation tool has emerged with superior precision and efficiency to address contemporary aeroacoustic challenges. This tool is called Fidelity LES, a high-fidelity CFD software developed by Cadence, a leader in fluid dynamics simulation. Fidelity LES was created to make high-resolution LES accessible to design engineers. It is optimized for the latest HPC hardware, including GPUs from NVIDIA and AMD. Its versatility is evident in its wide range of applications, from jet engine combustors and high-lift aerodynamics to vehicle external aerodynamics.

This white paper presents a thorough overview of Fidelity LES, its approach to addressing aeroacoustic simulation challenges, and its potential applications in industrial settings and academic research. In addition, we discuss the solver's computational methods, meshing techniques, post-processing tools, and case studies involving collaborations with Honda Research and Development (R&D) and NASA.

Predictive Computational Methods

Fidelity LES is engineered using sophisticated numerical methods that ensure high accuracy and stability. As listed in Table 1, this software has two primary solvers, including an ideal gas solver, which is suited for compressible, high-speed flow conditions. It can be used to simulate high-speed jet noise. Furthermore, the low-Mach (Helmholtz) weakly compressible solver is specifically designed to capture pressure fluctuations in low-speed flow situations, often encountered in aeroacoustics simulations. To accurately capture specific details like aeroacoustics, Fidelity LES uses a time-dependent technique to obtain the relevant flow characteristics.

	Ideal Gas Solver	**Low-Mach Solver**
Key Equations	Full compressible Navier-Stokes equations	Simplified Navier-Stokes equations, Helmholtz equation
Flow Regime	High-speed (transonic, supersonic, and hypersonic)	Low speed (subsonic)
Compressibility	Significant compressibility effects, variable density	Weak compressibility, near-constant density
Primary Focus	Resolving high-speed flow phenomena (e.g., jet noise, shock waves, and expansion fans)	Capturing pressure fluctuations and acoustic waves
Typical Applications	Aeroacoustics, high-speed aerodynamics (e.g., jets and rockets)	Aeroacoustics, low-speed aerodynamics

Table 1: Comparison of the ideal gas and low-Mach solvers available in Fidelity LES

An advanced LES model is implemented in Fidelity LES, which differentiates it from traditional CFD solvers. LES is a computational method used to resolve large-scale turbulent structures while modeling the smaller scales using sub-grid scale (SGS) models. Unlike conventional eddy-viscosity models, which often introduce artificial diffusion into the fluid domain, Fidelity LES is designed to minimize such inaccuracies. Central to its functionality are kinetic energy and entropy preserving (KEEP) schemes, designed to conserve kinetic energy and entropy, thereby fostering stability and low dissipation. As a result, no new entropy or losses in energy are artificially introduced by the numerical algorithm. Such a methodology leads to consistent flux discretization, eliminating the need for complex sensors, upwinding hybridization, or stability coefficient adjustments. The result is an LES model that offers unparalleled accuracy, mainly in capturing transient vortices and other complex flow phenomena.

Moreover, Fidelity LES has exhibited superior performance and precision compared to hybrid Reynolds-Averaged Navier-Stokes (RANS)/LES methodologies such as delayed detached-eddy simulations (DDES) due to its innovative wall-modeled LES (WMLES) paradigm. For boundary layer flows, the range of turbulent scales can vary drastically, as illustrated in Figure 1. The boundary layer is the region near the wall where the flow has a considerable gradient due to viscous effects. Consequently, the smallest scales near the wall require a very fine grid resolution. Therefore, directly resolving all the scales near the wall using direct numerical simulation (DNS) or wall-resolved LES (WRLES) calculations can be computationally expensive. To circumvent the computational challenge of directly resolving all the scales near the wall, the WMLES approach only resolves the outer layer structures away from the wall region while modeling the scales near the wall. This technique allows for the simulation of turbulent flows with boundary layers in a computationally efficient manner.

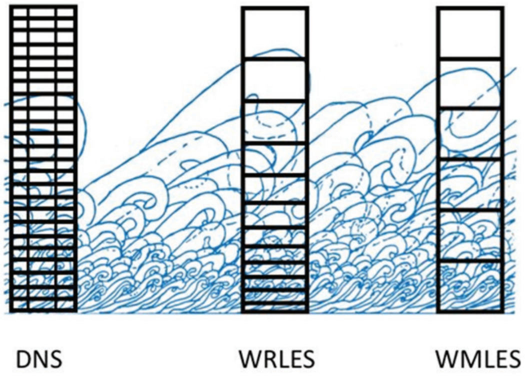


Figure 1: Grid resolution comparison of DNS, WRLES, and WMLES near the wall in the boundary layer

High-Quality Mesh Generation

Mesh generation is a key step in CFD, as the mesh quality can considerably influence the accuracy and efficiency of the simulation. Fidelity LES offers high-quality simulation results utilizing cutting-edge geometry cleanup and meshing features. The software's geometry preprocessor, Surfer, prepares 3D models for meshing by repairing surface quality defects and merging multiple geometries via Boolean functions. Users can also create 3D geometries using the built-in modeling feature without relying on external CAD software.

Fidelity LES is also equipped with a meshing tool named Stitch that uses clipped Voronoi diagrams (Figure 2) as the basis for its mesh generation. Voronoi-based meshing is a method of partitioning geometric space into cells around a specified set of points, where each cell is closest to a point relative to the other points. This approach allows for highly scalable mesh generation due to the uniquely defined global mesh, while each cell can be constructed using only local information. The Voronoi diagram method is computationally efficient and produces high-quality meshes well-aligned with complex geometries. This feature is beneficial for high-fidelity simulations where precise control over local mesh resolution is vital for describing intricate flow features (Brès et al., 2023c).

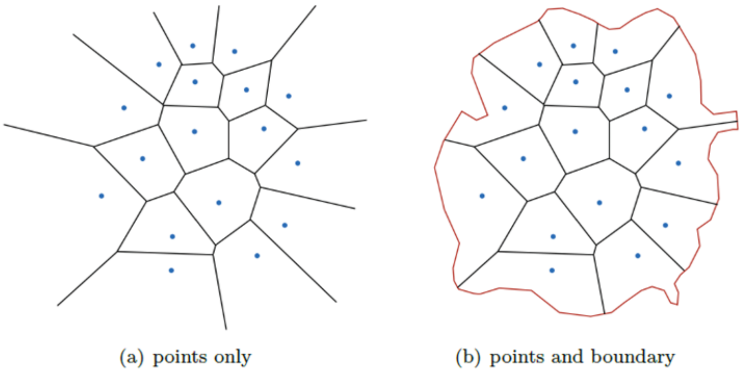


Figure 2: (a) 2D Voronoi diagrams given a set of generating points (blue dots) where the faces (black edges) act as perpendicular bisectors between the points. (b) A red bounding surface (red lines) "clips" the external cells, leaving internal cells, which are solely defined by the generating points (Brès et al., 2023c)

Furthermore, this software includes a moving mesh solver that can handle simulations with isolated rotating bodies. It assumes that the interface between moving and stationary regions slides, with no change in the domain volume. This simplification streamlines calculations by focusing only on updating the Voronoi diagram faces at the boundary between moving and stationary regions (Figure 3). As the rotating part shifts, the mesh in the stationary region remains unaffected, with information exchanged through the interface flux. This approach can be used to effectively model the interaction between rotating and stationary components, making it suitable for simulating rotating machinery like rotors and propellers (Brès et al., 2023c).

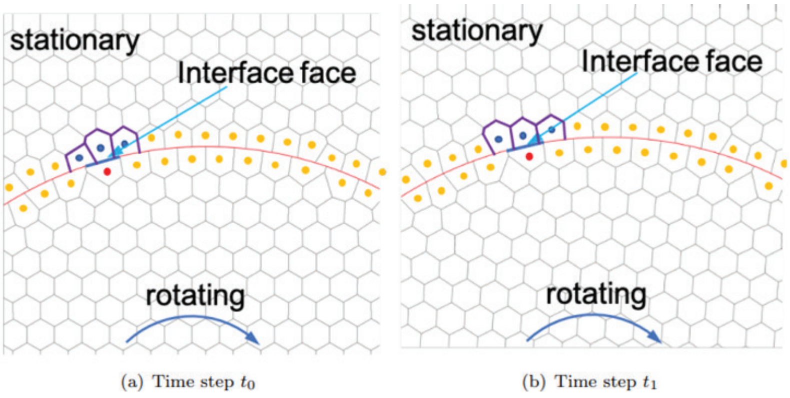


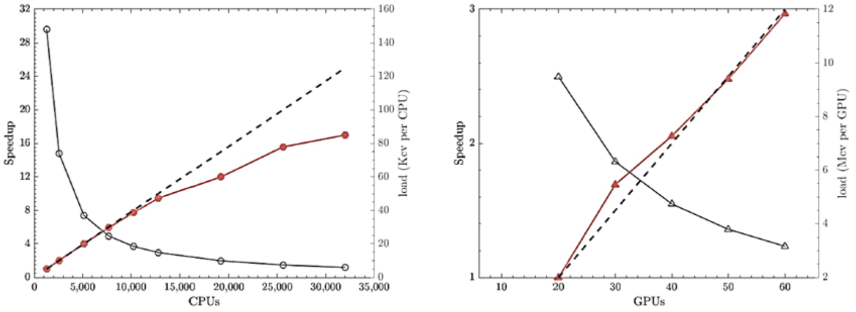
Figure 3: Rotating interface at two consecutive time steps (Brès et al., 2023c)

For applications like aerodynamics and aeroacoustics, analyzing the behavior of the flow near walls or boundaries is essential. Fidelity LES offers specialized meshing techniques for accurately resolving boundary layers, which is important for predicting wall-bounded noise sources. It only resolves the external boundary layer structures using the WMLES approach, allowing for flexible mesh dimensions. This tool also integrates skew-symmetric operators, ensuring stability and accuracy ranging between the 2nd and 4th order in distinct mesh regions.

In addition to its advanced meshing techniques, Fidelity LES supports parallel mesh generation. This feature enables the solver to distribute the meshing processes across multiple processors, substantially reducing the time required to generate large, complicated meshes. This software also gives users a high degree of control over mesh parameters, allowing for customization to meet specific simulation needs. Users can specify mesh density, element type, and other attributes to tailor the mesh to their problem's requirements.

Efficient and Scalable Solver

Large-scale aeroacoustic simulations require substantial computational resources. Fidelity LES has several features that make it highly efficient and scalable. It is optimized for GPU architectures, significantly reducing computational time compared to traditional CPU setups. As depicted in Figure 4, the computational speedup ideally scales with the number of GPUs. This is beneficial for large-scale simulations or scenarios where quick turnaround times are necessary.



(a) Scalability study on CPUs (AMD EPYC)

(b) Scalability study on GPUs (Nvidia V100)

Figure 4: Scalability study of the Fidelity LES Solver for the CPU-based version (•) and the GPU-accelerated version (▲) vs. ideal speedup (----) for source diagnostic test (SDT) fan configuration on a 190 Mcv mesh. The loading in Kcv per CPU (◦) and Mcv per GPU (△) is also displayed on the right vertical axis (Brès et al., 2023d)

Fidelity LES is designed for parallelization, enabling it to distribute the computational load efficiently across multiple processors or computing nodes. This feature allows the solver to scale on various hardware configurations, from local workstations and small clusters to supercomputers. It also incorporates sophisticated load-balancing algorithms to optimize the distribution of computational tasks. Thus, all processors are utilized effectively, minimizing idle time and enhancing overall computational efficiency.

Additionally, Fidelity LES makes optimal use of available memory, decreasing the need for excessive memory allocation. This is important for large-scale simulations where memory usage can be a limiting factor. The real-time monitoring of computational performance is also offered, allowing users to optimize the efficiency of long-running simulations through dynamic adjustments and resource reallocation.

Robust Post-Processing and Analysis

The value of a simulation is not just in its implementation but also in the insights that can be derived from its results. Fidelity LES comes equipped with a robust suite of post-processing and data analysis tools designed to help users extract meaningful information from their simulations, as illustrated in Figure 5.

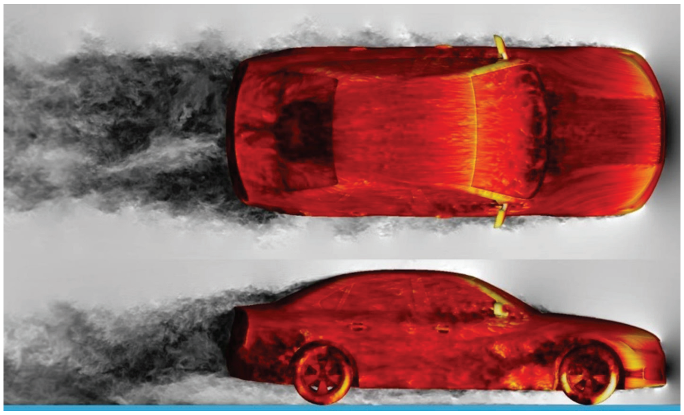


Figure 5: High-fidelity CFD simulation of the external aerodynamics of a car with Fidelity LES

Post-Processing

This software includes a set of post-processing features tailored for analyzing high-fidelity, time-dependent data. Users have the flexibility to extract specific data metrics, such as fluxes, point data, surface data, planar slices, and probability distributions. Beyond simple data extraction, Fidelity LES boasts a powerful expression parsing system, allowing users to transform raw simulation variables into more relevant metrics.

Quantitative Imaging

One of the distinctive features of Fidelity LES is its capacity to generate quantitative PNG images directly from simulations. This allows for rapid and parallel rendering of various data types, from planar and volume data to iso- and boundary surface data. Although these images can be viewed using standard image readers, what sets them apart is the custom metadata embedded within them. This metadata provides a direct link between each pixel and its corresponding location and value in the simulation space, giving the user a granular view of the complex 3D domain.

Ffowcs Williams-Hawkings Acoustic Predictions

Noise prediction from LES, especially far-field radiated noise, demands a hybrid approach. Fidelity LES first resolves the pivotal scales of turbulence in the noise-producing region. Subsequently, it computes the propagation of acoustic fluctuations from the near-field to the far-field analytically, using the data captured from the simulation. The Ffowcs Williams-Hawkings (FW-H) equation, a popular hybrid method, is seamlessly integrated into Fidelity LES for efficient and accurate noise predictions.

Modal Decomposition

Fidelity LES also contains dynamic mode decomposition (DMD) and proper orthogonal decomposition (POD) modal decomposition capabilities, applicable to both image and full-field data. These techniques are useful for breaking down flow and acoustic fields into their constituent modes. By isolating specific modes, researchers can focus on the most critical aspects of the aeroacoustics being studied. This is important for understanding the underlying mechanisms of noise generation and propagation.

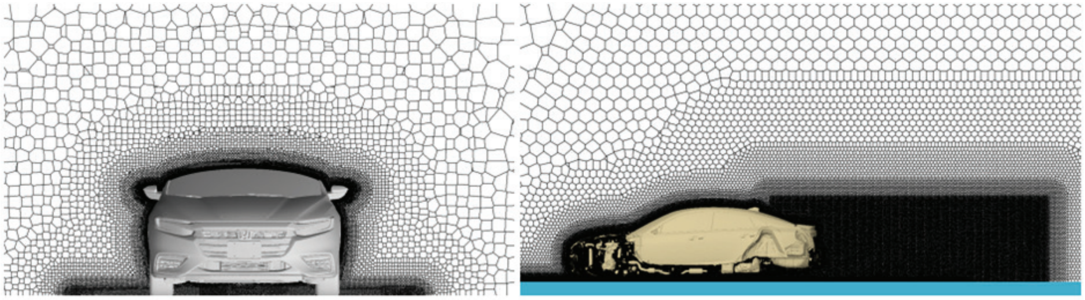
Beyond data analysis, Fidelity LES offers visualization tools for generating plots, contour maps, and other graphical representations of simulation data. Its Python application programming interface (API) and built-in expression evaluator lets users automate or customize processes as well as create variables and equations for calculations during post-processing. As a result, users can compute derived quantities like sound pressure levels, turbulence intensities, or other custom metrics relevant to aeroacoustic studies. These tools are essential for presenting findings in a clear and understandable manner, whether for academic publications, client reports, or internal reviews.

Applications in Aeroacoustics

Fidelity LES has been successfully applied to numerous aeroacoustic problems, demonstrating its versatility and effectiveness. This section discusses notable applications in aeroacoustics that highlight the solver’s capabilities.

Full-Scale Car Noise Simulations with Honda R&D

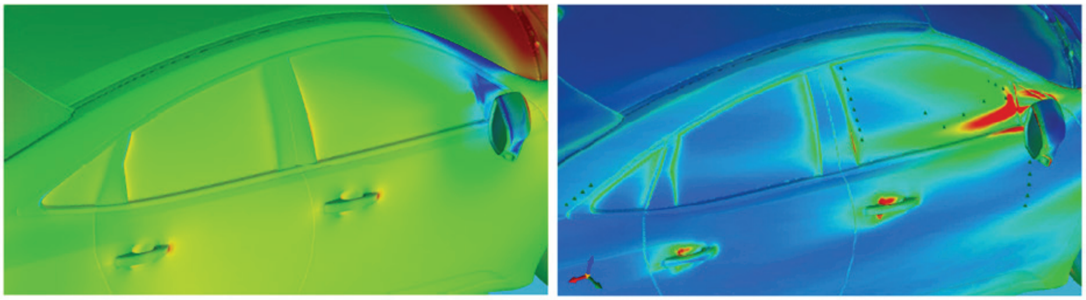
The aeroacoustic behavior of a full-sized sedan vehicle was simulated in collaboration with Honda R&D using Fidelity LES. The goal was to compare LES with wind tunnel measurements conducted at a speed of 120 kph with a 0-degree yaw angle. Two LES cases with 1- and 2-mm surface resolutions (Figure 6) were examined. The simulation with finer resolution (1 mm) captured more detailed turbulent structures and small-scale features, primarily around the A-pillar of the vehicle. This area was identified as a region with stronger vortex shedding in the refined case, which has implications for aerodynamic performance and noise generation (Brès et al., 2023b).



(a) Plane at $x = 0.7$ (b) Plane at $y = 0$ with internal mesh shown

Figure 6: Mesh visualization for the baseline setup with 2 mm surface resolution and 118M control volumes (Brès et al., 2023b)

The LES results (Figure 7) were validated through comparisons with wind-tunnel measurements of surface pressure fluctuations at specific locations on the vehicle, such as the hood, windshield, and side windows. Overall, the computational outcomes showed good agreement with experimental measurements, especially in capturing the pressure fluctuations and flow structures around the vehicle. Additionally, the computational cost and performance of CPU-based and GPU-accelerated versions of the solver were analyzed. The GPU-accelerated version was considerably more efficient, reducing the time-to-solution to about 1.5 hours on 32 Nvidia V100 GPUs compared to 6 hours on 2560 AMD EPYC CPUs. Computational efficiency is crucial for making aeroacoustic simulations more viable for industrial applications, including traditional automotive designs and emerging vehicle concepts like electric vertical take-off and landing (eVTOL) aircraft (Brès et al., 2023b).

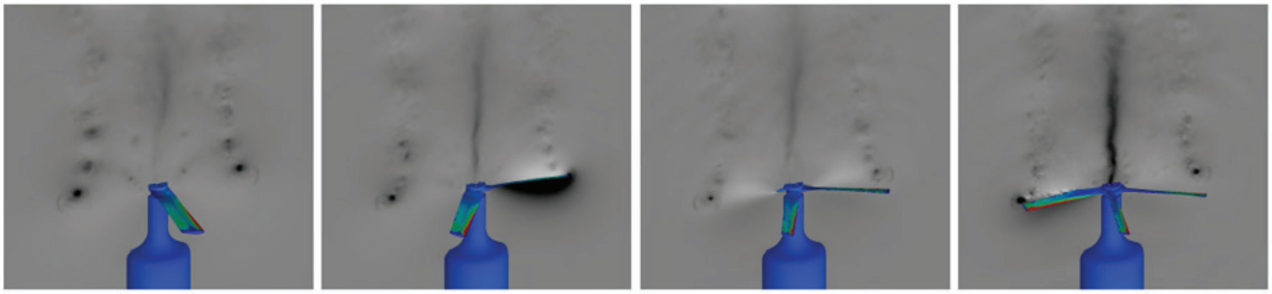


(a) $p_{avg} - p_0$, LES case Acs118M (b) p_{rms}, LES case Acs253M

Figure 7: Time average (left image) and rms (right image) of the surface pressure on right-hand side of the full-scale sedan car for the LES cases Acs118M (2 mm surface resolution) and Acs253M (1 mm surface resolution). The color ranges are (blue) −800 ≤ pavg−p0 ≤ 250 Pa (red) and (blue) 0 ≤ prms ≤ 100 Pa (red) (Brès et al., 2023b)

Aeroacoustic Analysis of Multiple Blade VTOL Rotors with Honda R&D

Researchers assessed the aeroacoustic performance of scaled multi-bladed VTOL rotors using the low-Mach Fidelity LES solver. The aim was to evaluate the accuracy and computational cost of high-frequency aeroacoustic simulations. The study involved simulating rotors with 2, 3, 4, and 5 blades (Figure 8) and comparing the results with measurements taken at Honda's wind tunnel facility. The Fidelity LES solver employed a finite volume LES code with low-dissipation numerical methods in an arbitrary Lagrangian-Eulerian moving mesh framework, making it well-suited for analyzing low-speed turbulent flows involving rotating bodies. Furthermore, the team leveraged a mesh generation paradigm based on 3D Voronoi diagrams, which is ideal for surface motion, and enables high-quality, body-fitted, conformal moving meshes. This approach significantly decreased the time and human interaction required to generate quality meshes for this high-fidelity application (Brès et al., 2023c).



(a) 2 blades (b) 3 blades (c) 4 blades (d) 5 blades

Figure 8: Visualization of the pressure field $-400 \le P - P_0 \le 400$ Pa in a plane through the axis of rotation for the different rotors. The surface pressure (color contours) is also shown (Brès et al., 2023c)

The simulations successfully captured the experimental trend of increasing high-frequency noise as the number of blades increased. There was good agreement with the experimental data in terms of blade passage frequency tone, broadband noise, and overall sound pressure level (Figure 9). Moreover, a proof-of-concept simulation of a full-scale eVTOL aircraft with eight VTOL rotors and two propellers was performed to demonstrate the LES modeling approach and evaluate the potential increase in computational throughput achievable with GPU acceleration. This study underscores the major advantages of Fidelity LES in predicting unsteady turbulent flows and their acoustic fields, especially for subsonic and supersonic jet noise. It also highlights the potential of Fidelity LES in advancing the optimization process by providing a cost-effective computational tool that can guide the design. Fidelity LES paves the way for quieter and more efficient rotor configurations for urban air mobility solutions (Brès et al., 2023c).

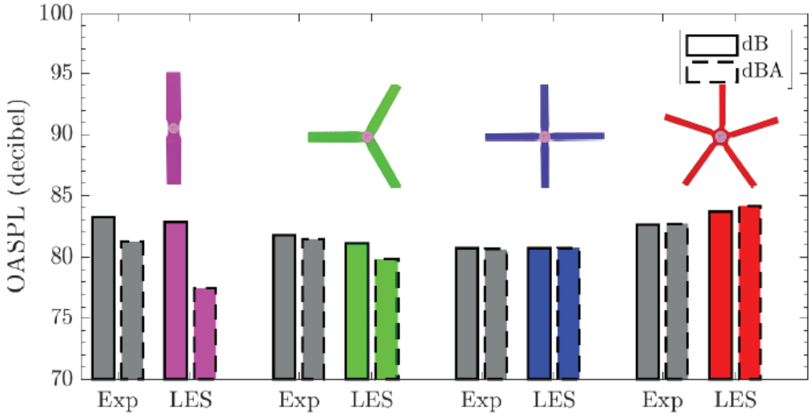
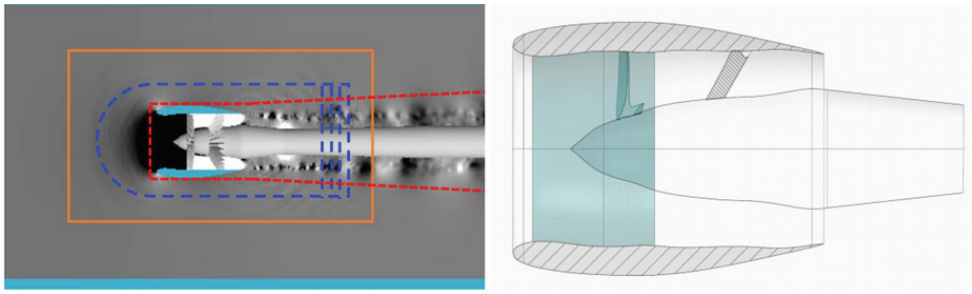


Figure 9: Overall sound pressure levels in dB and dBA for the experimental measurements (grey) and the LES predictions for the 2-bladed rotor (pink), 3-bladed rotor (green), 4-bladed rotor (blue) and 5-bladed rotor (red) (Brès et al., 2023c)

Fan Noise Diagnostic Testing with NASA

Fidelity LES was used to simulate NASA's fan noise source diagnostic test (SDT), a benchmark problem in the aeroacoustics field. The goal was to study the influence of different outlet guide vane (OGV) configurations on aerodynamic performance and noise characteristics of the fan. The computational setup (Figure 10) included the full annulus of the fan and OGVs, the nacelle, and the entire test section to prevent numerical artifacts induced by artificial periodicity or domain truncation. The unstructured meshes for stationary and rotating parts were generated through the computation of Voronoi diagrams, a robust and efficient paradigm for mesh motion. The simulations were performed at an approach condition where the fan operated at a reduced rotational speed of 7,809 rpm, equivalent to 61.7% of the design speed (Brès et al., 2023d).



(a) Overview of computational setup

(b) Definition of rotating part

Figure 10: Setup of the NASA SDT fan simulation: (a) zoomed-in view of the computational domain with the sponge region (outside of orange box) and the FW-H surfaces – s1 (blue) and s2 (red); (b) the division of the domain where the green part is in rotation (Brès et al., 2023d)

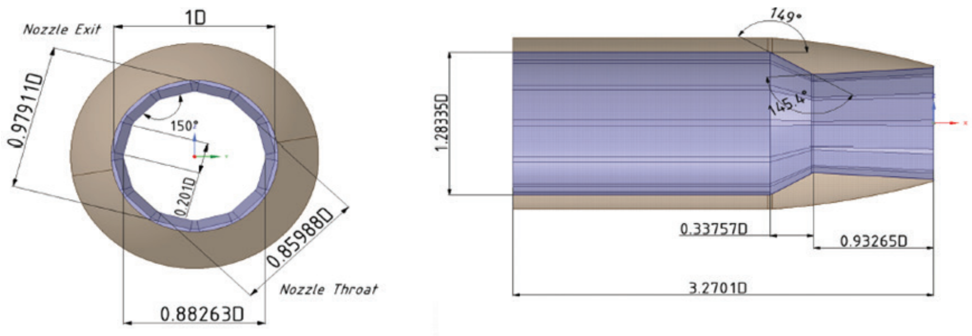
The low noise OGV configuration resulted in a notable reduction in the overall sound power level (OAPWL) by about 2 dB compared to the baseline and low count OGV configurations. This outcome was validated by experimental data. Moreover, the simulations accurately captured the noise mitigation effects of the low noise OGV. Despite the relatively modest mesh count and limited resolution on the fan blade, the OGV surface, and the tip gap, the simulations exhibited a high degree of agreement with the experimental measurements (Table 2), showcasing less than 0.5% relative error in certain aerodynamic efficiencies. The findings demonstrate the predictive ability of Fidelity LES. In future aeroacoustic studies, the aim is to enhance the solver's performance through strategies like input/output (I/O) optimization and leveraging newer generations of GPU hardware with GPU direct communication protocols (Brès et al., 2023d).

Case	Stage P_t ratio	Stage T_t ratio	Stage η_{ad}	$\dot{m}_C$ (kg/s)	OAPWL (dB)
Baseline OGV (NASA exp.)	1.154	1.049	0.860	26.54	125.7
Baseline OGV (LES)	1.154	1.049	0.856	26.53	124.2
Low count OGV (NASA exp.)	1.154	1.049	0.861	26.54	126.9
Low count OGV (LES)	1.154	1.049	0.860	26.55	124.6
Low noise OGV (NASA exp.)	1.153	1.049	0.857	26.44	124.1
Low noise OGV (LES)	1.154	1.049	0.856	26.55	122.7

Table 2: Comparisons of the stage performance (i.e., total pressure ratio, P_t, total temperature ratio, T_t, and isentropic efficiency, η_{ad}) and radiated noise for the baseline, low count, and low noise OGV configurations under the approach condition (61.7% of the design speed) between the experimental measurement and the LES on the 142 Mcv mesh (Brès et al., 2023d)

Supersonic Jet Noise Prediction with NASA

The acoustics of supersonic jets were investigated using Fidelity LES. This study leveraged LES to model the noise generated by highly heated, over-expanded supersonic jets with a military-style converging-diverging nozzle (Figure 11) under different thermal conditions: military power settings, afterburning conditions, and non-uniform inlet temperature. Initial comparisons with experimental data from NASA Glenn Research Center showed that the simulation accurately replicated critical flow features and noise levels, validating the LES approach. Subsequent simulations improved spatial resolution near the nozzle exit and incorporated a dual plug-flow profile to represent the core-bypass flow, enhancing simulation accuracy and reducing the noise prediction error to within 1–2 dB of experimental values (Brès et al., 2023a).



(a) Cross section

(b) Streamwise section

Figure 11: Nozzle schematic and dimensions (Brès et al., 2023a)

These results confirmed the fidelity of the LES model in capturing essential aerodynamic phenomena. Comparison simulations were conducted to analyze the noise profiles under standard afterburner conditions and the new non-uniform temperature setup (Figure 12). The results showed that the new setup could significantly reduce the peak overall sound pressure level and radiated power by 1.6 dB and 1.1 dB, respectively. This reduction is attributed to the altered flow mixing and shear layer dynamics. The positive outcomes suggest substantial promise for temperature non-uniformity as a noise mitigation strategy under realistic operating conditions. Future research will focus on refining the simulation accuracy by incorporating variable gas properties and exploring more complex temperature profiles to reduce jet noise. This work highlights the physics underlying jet noise and facilitates the development of effective noise mitigation techniques (Brès et al., 2023a).

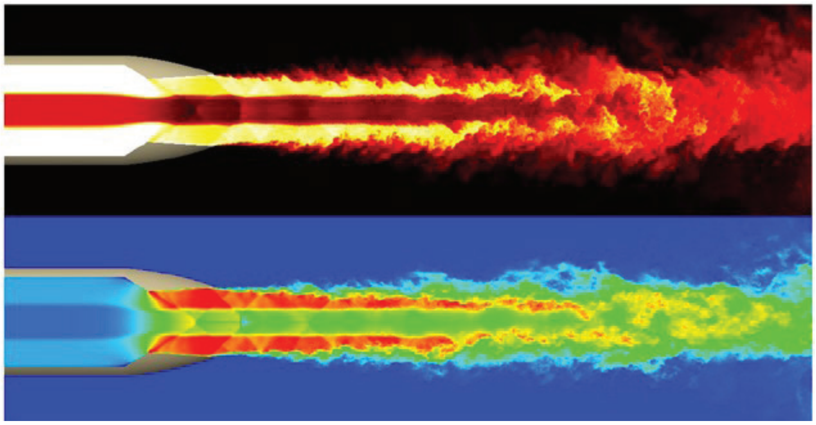


Figure 12: Instantaneous temperature T/T_∞ (top image) from 1 (black) to 5.5 (white) and velocity magnitude $|u|/C_\infty$ (bottom image) from 0.1 (blue) to 3.5 (red) for non-uniform inlet conditions (Brès et al., 2023a)

Conclusion

Fidelity LES has proven itself to be powerful and accurate software for aeroacoustic simulations. Its advanced computational methods, high-quality meshing techniques, and comprehensive post-processing capabilities make it a top choice for tackling complex aeroacoustic challenges. Its efficiency and scalability ensure that it can be effectively used across a range of hardware configurations, making it useful for industrial applications.

Moreover, the solver's flexibility and proficiency position it as an industry-leading tool for R&D. Cadence's successful collaboration with Honda R&D and NASA serves as a testament to the Fidelity LES solver's applicability in real-world engineering problems. It is a valuable asset for companies looking to optimize their products for aerodynamic and acoustic performance. Fidelity LES is also ideal for performing high-fidelity, innovative research in aeroacoustics that contributes to the advancement of the field.

The Fidelity LES solver's sophisticated algorithms and scalable architecture enable users to simulate various aeroacoustic problems in the automotive and aerospace industries. Whether you are an industry professional seeking to optimize product designs or a researcher looking to explore new frontiers in aeroacoustics, Fidelity LES offers the accuracy, efficiency, and scalability you need to achieve your objectives.

Additional Resources

For those interested in a more in-depth understanding of Fidelity LES, we highly recommend reading the referenced AIAA conference papers. These papers provide comprehensive insights into the solver's capabilities, methodologies, and real-world applications, providing a perspective that complements this white paper.

References

1. Brès, G. A., Towne, A., & Lele, S.K (2019). Investigating the effects of temperature non-uniformity on supersonic jet noise with large-eddy simulation. 25th AIAA/CEAS Aeroacoustics Conference, DOI: 10.2514/6.2019-2730.
2. Brès, G. A., Ivey, C. B., Philips, D. A., Bose, S., Miyazawa, M., Morishita, K., & Teramura, M. (2023). Aeroacoustic simulations of full-scale sedan vehicle towards interior noise predictions. AIAA AVIATION 2023 Forum, DOI: 10.2514/6.2023-3825.
3. Brès, G. A., Ivey, C. B., Philips, D. A., Bose, S., Teramura, M., Moriya, T., & Ambo, K. (2023). Large-eddy simulations of multi-bladed VTOL rotors for air vehicle aeroacoustic predictions. AIAA AVIATION 2023 Forum, DOI: 10.2514/6.2023-3938.
4. Brès, G. A., Wang, K., Emory, M., Ivey, C. B., & Bose, S. (2023). GPU-accelerated large-eddy simulations of the NASA fan noise source diagnostic test benchmark. AIAA AVIATION 2023 Forum, DOI: 10.2514/6.2023-4299.