Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46548

NOISE PREDICTION OF PRESSURE-MISMATCHED JETS USING UNSTRUCTURED LARGE EDDY SIMULATION

Yaser Khalighi[*], **Frank Ham, Parviz Moin**
CASCADE Technologies Inc.
Palo Alto, CA 94303

Sanjiva K. Lele
Dept. Mechanical Engineering
Stanford University
Stanford, CA 94305

Robert H. Schlinker
United Technologies Research Center
411 Silver Lane
East Hartford, CT 06108

1 Introduction

It is our premise that significant new advances in the understanding of noise generation mechanisms for jets and realistic methods for reducing this noise can be developed by exploiting high-fidelity computational fluid dynamics: namely large eddy simulation (LES). In LES, the important energy-containing structures in the flow are resolved explicitly, resulting in a time-dependent, three-dimensional realization of the turbulent flow. In the context of LES, the unsteady flow occurring in the jet plume (and its associated sound) can be accurately predicted without resort to adjustable empirical models. In such a framework, the nozzle geometry can be included to directly influence the turbulent flow including its coherent and fine-scale motions. The effects of propulsion system design choices and issues of integration with the airframe can also be logically addressed.

The literature on non-dissipative (sometimes called kinetic energy conserving) numerical methods for LES is substantial. In an important comparative study, Mittal & Moin (1997) illustrated the detrimental effect of upwind-biased schemes on resolved turbulence. Based on this and other similar studies, non-dissipative numerical methods can be shown to much more effectively capture the broad spectral content of turbulence. This is an attribute which is very important for noise prediction. Dynamic method for closing the sub-grid scale models based on the resolved flow was first proposed by Germano *et al.* (1991) and modified by Lilly (1992). Use of the dynamic method was extended to compressible flows by Moin *et al.* (1991) and to one-equation models by Ghosal *et al.* (1995). More recently, the dynamic method has been applied to Vreman's model Vreman (2004); You & Moin (2007). Implementing the dynamic method in the context of non-dissipative schemes results in a numerical approach with no tunable turbulence parameters, apart from the details of the mesh. Different groups who have attempted to predict the noise of turbulent jets using LES have had mixed success (see Ladeinde *et al.* (2008); Lo & Blaisdell (2008)). As reviewed by Bodony & Lele (2008), numerical dissipation, inadequate azimuthal resolution, and artificially thick near-nozzle shear layers were among the factors which contributed to poor predictions. In the work by Shur *et al.* (2005*a*,*b*); Spalart *et al.* (2007), a high-order, multi-block structured LES code was successfully used for predicting the jet noise. Despite the accurate prediction, due to the structured nature of the algorithm, the interaction of nozzle and flow was not directly included. The application of the method was, therefore, limited to simple nozzle design. To extend the use of LES as a design tool for jet noise reduction, since the nozzle geometry directly influences the turbulent flow inducing coherent and fine-scale motions, an unstructured mesh framework should be considered. Most recently, Mendez *et al.* (2009, 2010) have successfully applied unstructured LES scheme of Shoeybi *et al.* (2009) and predicted the noise emitted from supersonic jets and compared the result to the experiments carried out by Bridges & Wernet (2008). An important lesson learned from previous research on computational aeroacousitcs is that a numerical method suitable for accurate prediction of noise requires extra care in many different aspects. In general, sound waves contain a small amount of energy as compared to the flow itself and can be easily overwhelmed by numerical errors. For the same reason, sponge layers are required to prevent reflection of sound from outflow boundary conditions back to the compu-

[*]Email: khalighi@cascadetechnologies.com

tational domain (Bodony, 2005). More importantly, shock capturing schemes can severely attenuate sound waves if not applied properly (Mani *et al.*, 2009).

Here, an unstructured mesh framework is developed; in such framework the nozzle geometry directly influences the turbulent flow inducing its coherent and fine-scale motions, and the effect of propulsion system design choices can be logically addressed. Previously, this method was successfully applied to predict the flow and noise issued by a perfectly expanded supersonic nozzle. In practical applications the static pressure at the exit of the supersonic nozzle is generally not matched with the ambient pressure. 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, i.e., broadband shock-associated noise (BBSN) and screech. Both components preferentially radiate in the direction upstream to the jet flow and thus subject the airframe components and nozzles to potentially significant acoustic fatigue. In addition, the interaction of shock cells and turbulent plume plays a significant role in the mechanism of noise generated by a jet impinging on ground or a jet blast deflector (JBD). In one hand, it is known that excessive numerical dissipation has a detrimental effect on the quality of turbulent flow solution and sound obtained from LES; in other hand, local numerical dissipation is required to capture strong shocks in the flow. Therefore, a high fidelity LES tool suitable for capturing shock/turbulence interaction requires a careful implementation of the shock-capturing scheme. In this work we will present such LES tool and demonstrate the application of the method to heated and unheated pressure-mismatched jets issued from round nozzles. In addition, grid-sensitivity study for an unheated jet issued from a round nozzle will be presented. Farfield and nearfield noise in addition to flow statistics will be compared to experimental measurements conducted at UTRC; noise components associated with turbulent mixing and BBSN will be studied and their sensitivity to heating will be discussed.

2 Unstructured LES Technology

The large eddy simulations described in this paper were performed with the flow solver "CharLES". CharLES solves the spatially-filtered compressible Navier-Stokes equations on unstructured grids using a novel control-volume based finite volume method where the flux is computed at each control volume face using a blend of a non-dissipative central flux and a dissipative upwind flux, i.e.:

$$F = (1-\alpha)F_{central} + \alpha F_{upwind} \quad (1)$$

where $0 \leq \alpha \leq 1$ is a blending parameter. This blending approach is often the basis of implicit approaches to LES, where the blending parameter is selected as a global constant with a value large enough to provide all the necessary dissipation (and potentially much more). CharLES does *not* use the "implicit" LES approach – an explicit sub-grid scale model is used to model the effect of the unresolved scales on the resolved flow. To minimize numerical dissipation relative to implicit LES approaches, the value of α is allowed to vary spatially such that it can be set to zero in regions where the grid quality is good and the scheme based on the central flux is discretely stable and non-dissipative. In regions of less-than-perfect grid quality, however, the central scheme can introduce numerical instabilities that must be prevented from contaminating/destabilizing the solution by locally increasing α. The novel aspect of CharLES is its algorithm to compute this locally optimal (i.e. minimal) α, which will be described next.

A stable and non-dissipative differencing operator is a skew-symmetric operator, i.e. $D = -D^T$. If one constructs a differencing operator on a uniform Cartesian grid using polynomial interpolation, one produces a skew-symmetric operator naturally. On non-uniform and/or irregular grids, however, the application of polynomial interpolation to build accurate face fluxes will lead to a non-skew-symmetric differencing operator. It is this local lack of skew-symmetry that CharLES uses to scale the blending parameter α. Specifically, we use the row-norm of the symmetric part of the differencing operator D:

$$\alpha = c\,||(D_n + D_n^T)_i|| \quad (2)$$

where $c = 2$ is a constant chosen based on numerical tests. One significant advantage of this approach is that the blending parameter is purely grid-based, and can be pre-computed based on the operators only.

Because the underlying numerical method has minimal numerical dissipation, it is critical to employ a sub-grid model to account for the physical effects of the unresolved turbulence on the resolved flow. Two modeling options are available in the code: the dynamic Smagorinsky model (Germano *et al.*, 1991; Lilly, 1992; Moin *et al.*, 1991) and a dynamic version of Vreman's model (Vreman, 2004; You & Moin, 2007). For the large eddy simulations reported in this work, we used the Vreman model with constant coefficient set to the recommended value of $c = 0.07$, and constant turbulent Prandtl number $Pr_t = 0.9$ to close the energy equation.

In this work, strong shocks will be present for the pressure-mismatched conditions. Shocks, like sub-grid scale turbulence, are also sub-grid phenomena and thus require modeling to account for their effect on the resolved flow. Unlike sub-grid scale turbulence they are localized in the flow, and a surgical introduction of modeling is potentially more appropriate. CharLES uses a hybrid Central-ENO scheme to simulate flows involving shocks.

The scheme has three pieces:

1. A central scheme, described previously,
2. An scheme appropriate for computing a flux across a shock,
3. A hybrid switch, which detects where shocks are present in the flow, and activates the shock-appropriate scheme.

For the shock-appropriate scheme, CharLES uses a 2nd-order ENO method to perform reconstructions (Shi *et al.*, 2002), and the HLLC approximate Riemann solver to compute the flux (Harten *et al.*, 1983). The ENO method is fully unstructured, and as such must consider a potentially large number of candidate stencils. In regions of nearly uniform orthogonal grids, however, the number of candidate stencils reduces to two stencils per face-side (i.e. two for the left side value and two for the right-side value at each face), substantially reducing the cost of the method over a large fraction of the grid.

The hybrid switch is based on the method developed originally by Hill & Pullin (2004), where the magnitudes of the smoothness parameters computed as part of the ENO reconstructions are compared to identify the presence of flow discontinuities.

For prediction of far-field noise we developed a noise projection module based on the early work of Ffowcs Williams & Hawkings (1969) and its extension by Spalart & Shur (2009). Figure 1 demonstrates a flow snapshot and the control surface that encloses the sources of sound.

3 Simulation of Flow and Noise for Supersonic Jets

The computation model were designed to mimic as close as possible to the jets at UTRC's acoustic research tunnel (ART) facility. The same converging-diverging (CD) nozzle geometry was chosen for the computations to match the experiment. The 3" diameter CD nozzle was designed using a method-of-characteristics to provide ideal expansion or shock free flow at the nozzle exit for $M_j = 1.5$. Baseline mean flow data for perfectly-expanded nozzle was acquired to document the potential core length and sonic point in the exhaust stream. Radial profiles of total pressure, total temperature, and static pressure were acquired using a multi-probe from which Mach number, static temperature, and velocity were calculated. Surveys were conducted in the horizontal and vertical direction for the round nozzle to confirm that the traverse was aligned with the jet centerline. Centerline decay measurements along the jet axis were also acquired.

The computational domain is shown in figure 1. As shown, part of the nozzle geometry is included in the simulation domain. A constant plug-flow is applied to the inlet of the nozzle such that the desired Mach number and the temperature ratio are achieved at the nozzle lip. It should be noted that we "assume" that the flow issued from the nozzle is laminar [1]. Consequently, the grid resolution inside the nozzle is only adequate for a laminar flow. A slight coflow is applied to the jet surroundings to simulate the wind tunnel Mach number of $M_t = 0.1$.

As shown in figure 1, a sponge layer is applied at the outlet of computational domain by switching the numerical operators to low-order dissipative discretization. By using this method, the turbulent structures and sound waves will be damped before approaching the outlet boundary.

The acoustic projection surface described earlier is also shown in figure 1. To avoid the spurious noise caused by passage of flow structures through the end cap, the method introduced by Shur *et al.* (2005*a*) is applied; 15 end-caps spanning from $x = 20D$ to $x = 30D$ end-cap are used to eliminate the uncorrelated (erroneous) sound. A sensitivity study of computed sound to the size of the acoustic projection surface and number of end-caps was carried out; similar conclusions to studies of Mendez *et al.* (2009) and Shur *et al.* (2005*a*) were obtained.

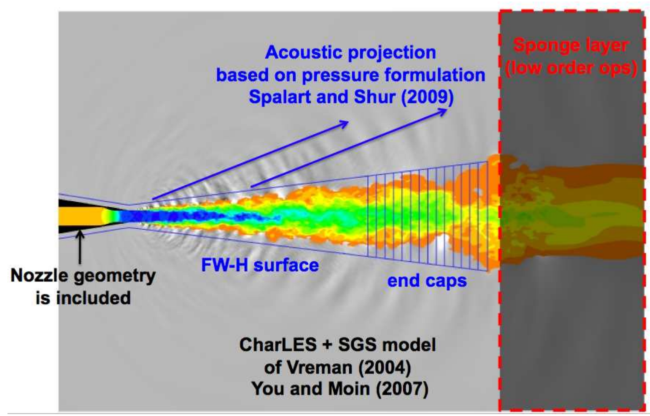

Figure 1. LES computational domain. Axial velocity field is shown in color, pressure is shown in grayscale.

Figure 2 demonstrates two sets of LES prediction stations corresponding to UTRCs experimental set up in which near field and far field microphones were used as reported by Schlinker *et al.* (2008). The near field stations, annotated as $P_1 - P_8$, are based on the UTRCs detection of instability wave generated large-scale turbulence structures in the jet shear layer, generally accepted to be the source of aft-angle noise. The sensors are located in the hydrodynamic near field of the jet shear layer. The jet hydrodynamic near field has been demonstrated by UTRC to be the sound "source" containing the traveling wave pressure signature responsible for noise radiating to the far field in the aft direction. This was confirmed by Reba *et al.* (2009) using the

[1] In the experiment, it is not known wether the flow issued immediately after nozzle is laminar or turbulent.

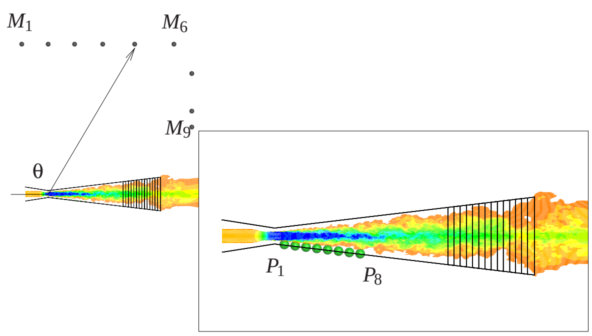

Figure 2. FWH surface and two sets of microphones used for calculation of noise; P_1 - P_8 are nearfield pressure probes; M_1 - M_9 are farfield microphones.

measured instability wave packets and projecting them to the far field microphone stations, $M_1 - M_9$.

The nearfield noise at each prediction station ($P_1 - P_9$) in figure 2 is calculated by recording the pressure signal from simulation on 48 equally-spaced azimuthal points. The sound spectrum is the average of spectra obtained from these azimuthal points. Farfield sound, at $M_1 - M_8$, is calculated and averaged for 120 equally spaced azimuthal points. Three jet operating conditions are considered in this work:

1. **Unheated pressure matched jet** This set point matched operating condition B118 of Schlinker *et al.* (2008). This case serves as our baseline case for validation purposes. We have presented some of the results earlier (Khalighi *et al.*, 2010). In this work we present grid-sensitivity study and a further refined LES calculation. In this calculation, LES mesh consists of 42 M unstructured grid cells which is significantly larger than finest case (13M grid cells) in the previous study.
2. **Heated pressure mismatched jet** For this case, we used the same nozzle designed for $M = 1.5$; however, we selected the nozzle pressure ratio for a jet operating at $M = 1.35$. The temperature ratio for this jet is $T_r = 1.734$.
3. **Unheated pressure mismatched jet** We used the same nozzle designed for $M = 1.5$; the nozzle pressure ratio for a jet operating at $M = 1.35$ and the temperature ratio for this jet is $T_r = 1.0$.

The objective of simulating operating conditions 2 and 3, in addition to validation of the LES framework in the presence of strong shocks, is to study the sensitivity of noise components associated with turbulent mixing and BBSN will to heating.

4 Preliminary results and ongoing work

One of the objectives in this work is to establish best practice LES; i.e., to provide guidlines for designing the mesh and selecting the simulation parameters. Accordingly, we designed a controlled mesh and repeated the baseline simulation for set point B118 carried out earlier (Khalighi *et al.*, 2010). A contour plot of instantaneous temperature is shown in Figure 3. This plot clearly shows more crisp and detailed turbulent structures than our previous results obtained from the finest mesh. The near-field sound obtained from this simulation is shown in Figure 4 and compared to the results previously obtained the medium mesh as well as UTRC's experimental measurements. This figure shows improved agreement with experimental measurements in a broader frequency range. The far-field noise for fine mesh is shown in Figure 5. These results are clearly improved and the sound spectra are extended to higher frequencies than the medium mesh.

Here, we show the preliminary solution of the heated pressure mismatched jet. For this case, we used the same nozzle designed for $M = 1.5$; however, we selected the nozzle pressure ratio for a jet operating at $M = 1.35$. The temperature ratio for this jet is $T_r = 1.734$. This jet is being simulated using the fine mesh. A snapshot of this flow is shown in Figure 6. The turbulent structures are visualized by showing the contours of temperature (in red-scale) and sound is visualized by contours of pressure (in gray-scale). Shock cells, fine turbulent structures are clearly visible in this figure. In addition, sound waves emitted to downstream and upstream of the jet are clearly shown. The former is caused by large scale structures while the latter is connected to the interaction of turbulent structures and strong shocks. Figure 7 demonstrates the instantaneous temperature field and the cuts normal to the axis of the jet; development of turbulent structures from small scale azimuthal structures in the early stages of shear layer till closure of potential core is clearly shown in this figure. The experiment corresponding to this jet condition is being conducted at UTRC. Concurrently, simulations of heated and unheated pressure mismatched cases are underway. After collecting flow statistics, near-field sound as well as far-field sound will be compared to experimental measurements. In addition, sound field will be decomposed to BBSN and turbulent mixing components. Sensitivity of each component to heating will be studied.

5 Acknowledgement

This work is supported by NAVAIR STTR program under grant number N68335-07-C-0017.

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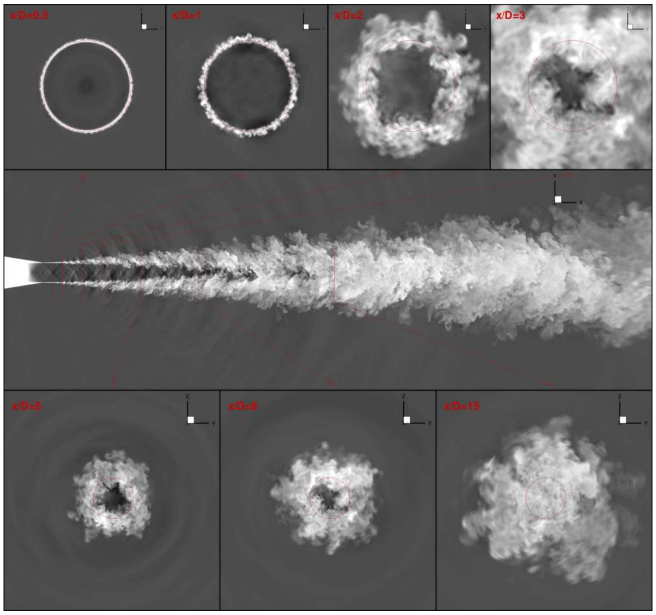

Figure 3. Contour-plot of instantaneous temperature for a perfectly expanded isothermal jet at $M = 1.5$. Temperature field for slices normal to the axis of the jet is also shown in top and bottom subfigures. In each subfigure, a circle with diameter of nozzle exit diameter is shown.

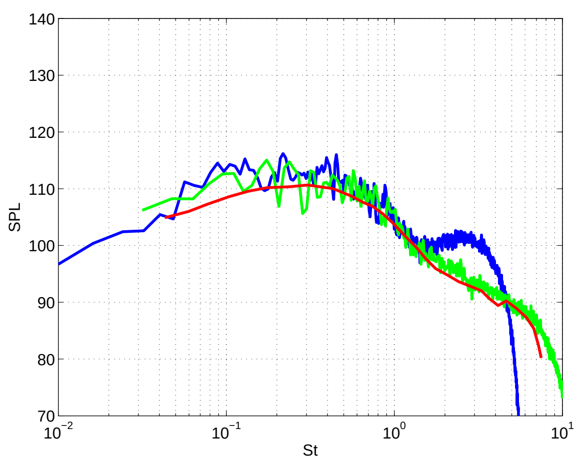

Figure 4. Comparison of near-field sound for B118 at nearfield microphone P_6.——— ,Experiment;——— ,medium LES;——— ,fine LES

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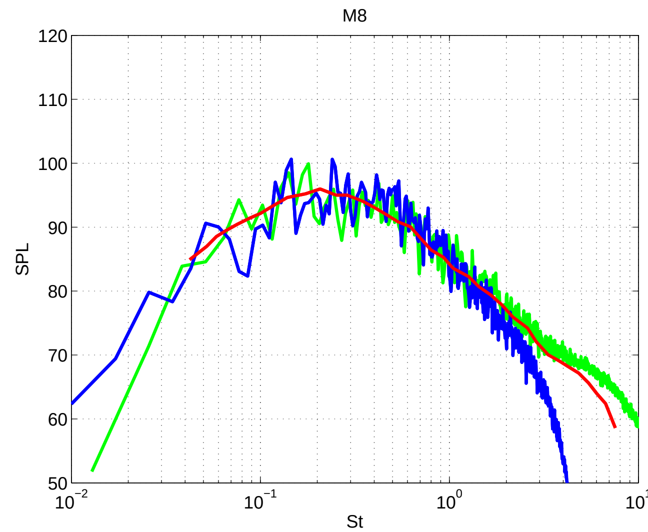

Figure 5. Comparison of far-field sound at M_8 for B118.——— ,Experiment;——— ,medium LES;——— ,fine LES

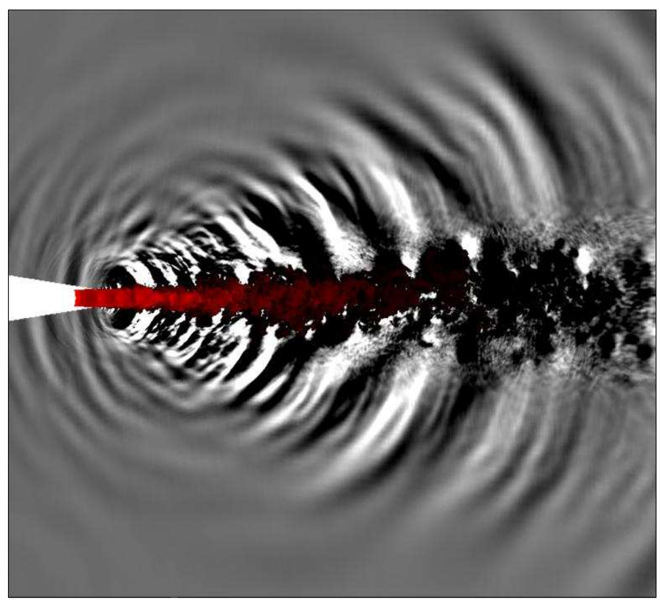

Figure 6. Instantaneous temperature (in red-scale) and pressure (in gray-scale) fields for an over-expanded jet, with temperature ratio of $T_r = 1.743$. The nozzle is designed for at $M = 1.5$; however the pressure ratio corresponds to $M = 1.35$.

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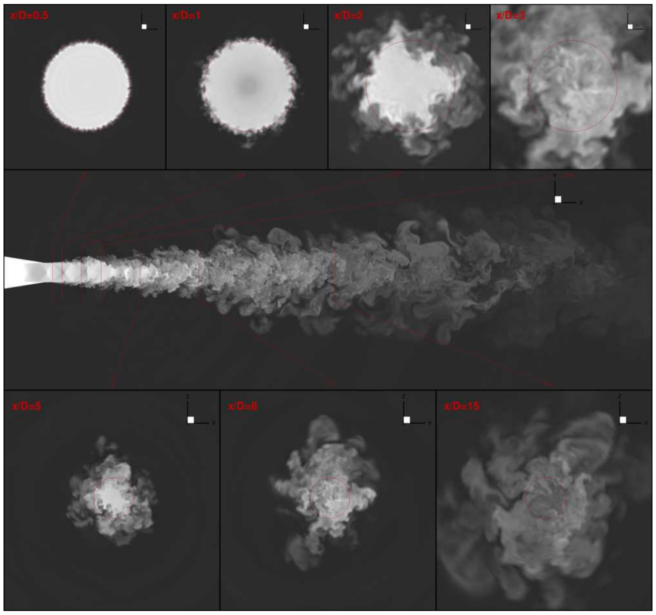

Figure 7. Contour-plot of instantaneous temperature for an over-expanded jet, with temperature ratio of $T_r = 1.743$. The nozzle is designed for at $M = 1.5$; however the pressure ratio corresponds to $M = 1.35$. Temperature field for slices normal to the axis of the jet is also shown in top and bottom subfigures. In each subfigure, a circle with diameter of nozzle exit diameter is shown.

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