LES-Based Numerical System for Noise Prediction in Complex Jets

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Abstract An overview is presented of a non-empirical CFD/CAA numerical system for jet noise prediction developed by the joint US – Russia team since 2002. Key elements of the system are discussed and examples are considered of its application to flow and noise computation for a wide range of cases that progress in the direction of the complete simulation of exhaust jets from real airliner engines.

1 Introduction

Reductions of the noise generated by turbulent exhaust jets behind aviation engines are of great practical importance since this type of aerodynamic noise is the main contributor to aircraft noise at take-off. Not surprisingly, during the last decade intense efforts have been invested in a search for efficient improvements in this area. As a result, a number of technical devices have been proposed and tested, but as of today the "target" value of external aircraft noise reduction by 10 EPNdB without excessive penalties is still far from reached. To some extent, this is caused by the absence of a reliable computational tool for jet noise prediction.

This work presents the status of such a tool, developed in the course of a long-standing collaboration between the scientists and engineers from the Boeing Company on one side and the R & D Company "New Technologies and Services" and St.-Petersburg State Polytechnic University, on the other side. This is an LES-based CFD/CAA numerical system which is ultimately aimed at predicting the aerodynamic characteristics and the noise of jets of real airliner engines with engineering accuracy of 2–3 dB, while having no empiricism and a general-geometry capability.

The problem of LES-based prediction of the noise generated by turbulent jets presents a great challenge, in terms of both numerics and physics, primarily because of the need to resolve multiple turbulent and sound scales and, also, because of the complexity of combining turbulence and far-field acoustics. The difficulties are

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aggravated by many non-trivial flow features, such as complex aerodynamics of the jets from non-circular and dual-stream nozzles, strong temperature variations, the presence of shocks (in case of imperfectly expanded supersonic jets), etc. These highlight the importance of a number of "strategic" decisions that are needed for a successful noise computation. They include the choice of the numerical scheme; the configuration of the computational domain, grid topology, and boundary conditions; the Subgrid-Scale (SGS) model (if any); the approach to reproducing transition to turbulence, etc. The same is true regarding the choice of an optimal method of far-field noise extraction from an LES in a confined computational domain.

The paper outlines the most important of these strategic decisions made in the numerical system we have developed and presents a range of "academic" and applied jet-noise studies demonstrating its current capabilities.

2 Overview of the Developed Numerical System

A detailed description of the numerical approach the system is based on is given in [2, 6, 8], and here we only briefly outline its salient features.

As far as numerics are concerned, the system is implemented within a general-purpose structured multi-block massively parallel Navier – Stokes solver (NTS code [7]), which uses implicit 2nd order time integration and dual time stepping. The approximation of the inviscid fluxes is based on the flux-difference splitting method of Roe and employs a weighted (4th-order centered and 5th-order upwind-biased) scheme in the turbulent region and acoustic near field coupled with a "pure" upwind-biased one outside that region. The weight of upwinding is chosen to keep numerical dissipation at the lowest level sufficient to prevent numerical instabilities introduced by nonlinearities, grid stretching, and other sources.

A major element of the algorithm used for treatment of jets with shocks is a simple and robust method of automatic local activation of flux-limiters which, to a considerable extent, permitted to reconcile the contradictory demands of shock capturing and resolution of fine-grained turbulence in LES and for the first time allowed satisfactory predictions of the spectral and integral characteristics of the far-field noise of under-expanded jets in a wide range of pressure ratios [3, 5, 12].

The grids used in the simulations have two overlapping blocks (additional artificial blocks are introduced to better make use of parallel processors). The inner, Cartesian, block is introduced to avoid a singularity at the axis of the cylindrical coordinates, and the outer, O-type, block allows a good control of the grid density and, in particular, grid-clustering within the thin shear layer, the latter being of crucial importance for representation of the fine-scale turbulence and therefore the high-frequency part of noise spectrum.

One of the key elements of the system is an original two-stage simulation procedure with a coupled nozzle/jet plume RANS computation, in the first stage, and LES of the jet plume alone, in the second stage. The approach has proven to reproduce the effect of the internal nozzle geometry and maintain realistic boundary layers without the extreme cost of the full coupled nozzle-plume LES [5].

For the turbulence simulation in the second (LES) stage of the computations, our current choice is to de-activate the Subgrid-Scale (SGS) model and to rely on the subtle numerical dissipation of the slightly upwind scheme, a strategy which is compatible with the spirit of LES, away from walls. Although an approximation, this approach ensures a rapid transition to turbulence in the jet shear layers, which is a key prerequisite for an accurate noise prediction at realistic (i.e., high) Reynolds numbers. A rigorous approach would be resolving the fine-scale turbulent structures of the nozzle boundary layers that seed the shear layer, but at the practical Re values this is far out of reach even with the most powerful modern supercomputers (see, e.g., [9]). An alternative approximate approach (explicit LES combined with artificial inflow forcing, as employed in many other jet studies) was rejected to avoid the creation of parasitic noise and especially the introduction of a number of arbitrary parameters. Note that our results without forcing certainly benefit from having thin boundary layers at the high Re, which reduces the extent of the unrealistic transition region, and the azimuthal correlation scale.

Finally, for the far-field noise extraction, Lighthill's acoustic analogy in the form of the permeable Ffowcs-Williams and Hawkings surface integral method is used. In contrast to the Kirchhoff approach, which could be the other practical option, it allows the placement of the control surface in the immediate vicinity of the turbulent region (in the inviscid but non-linear near-field) and, therefore, the confinement of the fine-grid area needed for turbulence resolution exactly to this turbulent area thus minimizing the loss of quality of the waves before they reach the surface, particularly for the higher-frequency waves in the near-nozzle area.

The control FWH surfaces have a shape of a tapered funnel with a "closing disk" at the downstream end which turbulence necessarily crosses, in violation of the assumptions of the quadrupole-less FWH approach. The inaccuracy caused by this violation is drastically reduced by a change of variables [2, 8] proved to be much more efficient than simply omitting the disk from the integral ("opening" the control surface) as is done in many FWH-based jet noise studies.

3 Current System Capabilities

The numerical system briefly outlined above has now reached a good level of confidence over a wide range of both flow conditions and geometries, as demonstrated by numerous examples of jets aerodynamics/turbulence and noise computations presented in [2–6, 12, 13].

In terms of flow conditions, the system has been shown capable of predicting the noise of subsonic and supersonic exhaust jets in the full temperature range of interest for commercial aviation. As applied to simple round jets, this is illustrated by Figs. 1 and 2, which present results of the computations [4, 12] for the cold subsonic $M = 0.9$ and hot sonic strongly under-expanded jets, respectively.

Particularly, Fig. 1 demonstrates a clear trend to grid-convergence of the predicted noise spectra and a distinct improvement of their agreement with

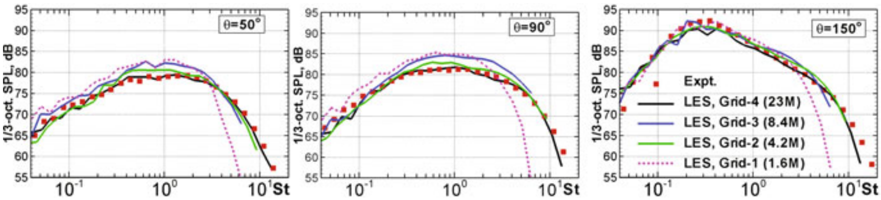

Fig. 1 Effect of grid on 1/3-octave noise spectra of cold M = 0.9 jet (data from [10])

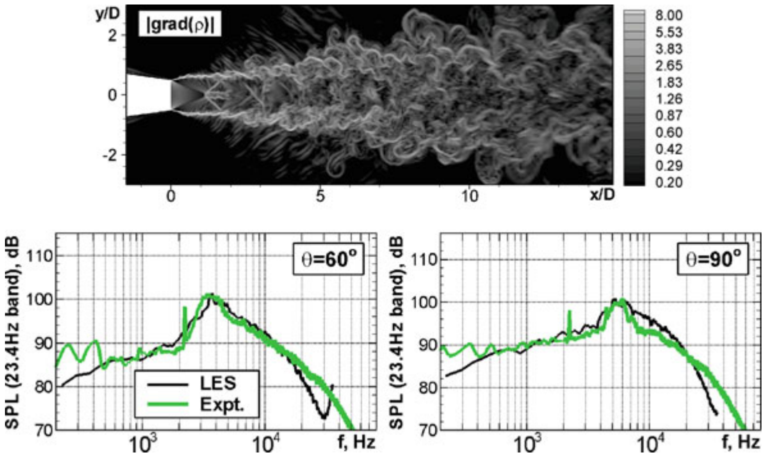

Fig. 2 Instantaneous density gradient field ("numerical Schlieren") and narrow-band noise spectra of a hot under-expanded sonic jet (data from [10])

measurements when the computational grid is refined. On the finest grid with around 23 million cells quite affordable nowadays, the approach ensures a reliable resolution of the spectra up to diameter-based Strouhal numbers of about 12 (compared to St = 2 on the coarsest grid with 1.7 million cells), which is already not crucially far from the range of St = 15–20 required by practice. This supports physical plausibility and numerical efficiency of the proposed simulation strategy and suggests that for the practically meaningful Re numbers and frequencies, the fully coupled nozzle-plume LES capable of "creation" of LES-content in the incoming boundary layer but unaffordable in terms of required computational resources is not really indispensable.

For the shocked jet shown in Fig. 2, one can see that the spectral characteristics of the noise including its broadband shock-associated component are predicted fairly well, thus providing an indirect evidence that essential features of shock-turbulence interaction (illustrated by the upper frame in the figure) are captured in the simulation.

In terms of geometries of exhaust systems that can be treated in the framework of the developed numerical tool, they now include dual nozzles, with stagger and with an external core plug, i.e. virtually fully reproduce the real exhaust jets from

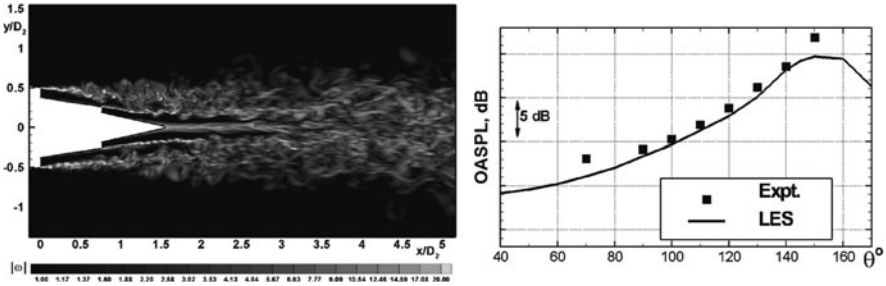

Fig. 3 Instantaneous vorticity in the meridian plane and overall sound directivity of dual-jet exhaust system with extended center body (data from [1])

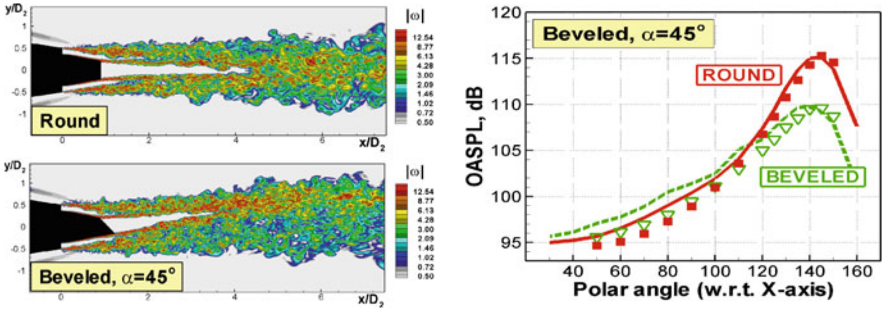

Fig. 4 Effect of core nozzle exit beveling on instantaneous vorticity and overall sound directivity of dual jet in $M = 0.2$ external stream (data from [11])

modern turbofan aviation engines (this is not to imply that full industrial cases, meaning an installed engine with pylon, wing and flaps, have been treated yet). Different noise-reduction devices such as fan-flow deflecting vanes, chevrons, beveled nozzles, and micro-jets injected into the main jet are also routinely treated [4–6, 13]. Some examples of prediction of flow and noise for such "complex" jets are shown in Figs. 3 and 4.

As seen in the figures, the accuracy of the noise prediction even with relatively coarse grids (up to 5 million nodes) is close to the "target" accuracy of 2–3 dB for both the integral jet noise and its spectral characteristics (not shown) up to a diameter-based Strouhal number ranging from 3 to 5, depending on the jet's parameters.

Thus it can be concluded that at this stage, the challenges associated with the reliable jet noise prediction appear to have been largely mastered, and the CPU power to be the essential obstacle to unrestricted performance. Remaining obstacles and areas for sustained attention in further work are: better representation of transition to turbulence in the jets' shear-layers within the two-stage RANS-LES computational approach and addressing the full geometry complexity of industrial flows, which have a number of additional geometry features (pylons, heat shields, vents, etc.).

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