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# Computing Jet Screech—A Complex Aeroacoustic Feedback System

Ching Y. Loh
Taitech, Inc., Brook Park, Ohio

Lennart S. Hultgren
Glenn Research Center, Cleveland, Ohio

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Ching Y. Loh
Taitech, Inc., Brook Park, Ohio

Lennart S. Hultgren
Glenn Research Center, Cleveland, Ohio

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Ching Y. Loh
Taitech, Inc.
Brook Park, Ohio 44142

Lennart S. Hultgren
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

**Abstract.** The space-time conservation-element and solution-element method is employed to numerically study the near-field axisymmetric screech-tone noise of a typical underexpanded circular jet issuing from a sonic nozzle. For the computed case, corresponding to a fully expanded Mach number of 1.19, the self-sustained feedback loop is established without artificial means. The computed shock-cell structure, acoustic wave length, screech tone frequency, and sound pressure levels are in good agreement with existing experimental results.

## 1 Introduction

Underexpanded supersonic jets radiate mixing noise, broadband shock-associated noise, as well as very loud discrete screech tones under certain conditions. Screech is of particular interest not only because of general noise-reduction concerns, but also because of potentially destructive structural interaction leading to sonic fatigue. Many experimental and theoretical investigations of jet noise have been carried out, see the review papers [1,2] for a comprehensive discussion. Mixing noise is directly associated with large-scale structures, or instability waves, in the jet shear layer; whereas, broadband shock-associated noise and screech tones are associated with the interaction of these waves with the shock-cell structure in the jet core. The screech tones arise because part of the acoustic waves generated by the wave/shock-cell interaction propagate upstream and re-generate the instability waves at, or in the vicinity of, the nozzle lip. This feedback loop leading to distinct screech tones is sensitive to small changes in the system conditions, and its explanation is to date mostly based on experimental observations, see [1,2].

Jet noise is a challenging topic in computational aeroacoustics – in particular, near-field noise computation in the presence of shock cells in the jet core – and reliable direct numerical simulation of jet screech noise has up to quite recently not been feasible. It imposes stringent requirements that the scheme must be able to: (i) handle shock waves, (ii) resolve acoustic waves with low dispersion and dissipation errors, (iii) resolve the instability waves in the jet shear layers and their interaction with the core shock-cell structure and (iv) have an effective non-reflecting boundary condition. Successful direct computation of screech for circular jets have been carried out by Shen and Tam [3,4] using the well-known DRP scheme and by the present authors [5] using the recent space time conservation element and solution element method, CE/SE, [6,7]. Further direct simulation of screech is presented below using the axisymmetric CE/SE Navier-Stokes scheme. The method is described in detail in [5,6].

## 2 Numerical Method

In general, the CE/SE method systematically solves a set of discretized (second-order accurate in both space and time) *integral* equations derived directly from the physical conservation laws and naturally captures shocks and other discontinuities in the flow. Both dependent variables and their derivatives are computed simultaneously. As a consequence, the flow vorticity can be obtained without reduction in accuracy. Non-reflecting boundary conditions (NRBCs) are also easily implemented because of the flux-conservation formulation.

With an unstructured grid, the CE/SE procedure is easily adapted to complicated geometries. Here, an unstructured triangle grid is used. Figure 1 shows a typical triangle cell, $\Delta$ABC, with O being its center and D, E, F being the centers of its three neighboring cells. The flow variables at the current time level

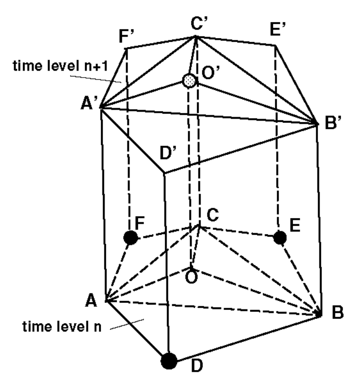



**Fig. 1.** CE/SE unstructured grid: hexagon cylinder ADBECFA-A'D'B'E'C'F'A' containing three CEs OADBO-O'A'D'B'O', OBECO-O'B'E'C'O', OCFAO-O'C'F'A'O'

$n$ are stored at the center of each triangle cell. Three quadrilateral cylinders (conservation elements, CEs) are formed by the edges that connect the vertices and the center of the triangle and its three neighbors. The solution elements, SEs, are the interfaces between the CEs. An integral form of the conservation laws is applied to the hexagon cylinder that consists of these three quadrilateral cylinder conservation elements and explicitly determines the full solution at O' at the new time level $n+1$ using only information stored at D, E, and F (no extrapolations/interpolations across a stencil of cells are needed). Discontinuities are allowed to occur in a conservation element. Details about the unstructured CE/SE method can be found in [8]. The weighted $a$-$\epsilon$ CE/SE scheme is used with the weighting parameter $\alpha = 1$ and $\epsilon = 0.5$ in the present computations.

## 3 Computation and Comparison with Experiment

Figure 2(a) shows the geometry of the convergent nozzle in Panda's experiment [9]. The flow is choked (i.e. Mach number $M = 1$) at the nozzle exit. The jet Mach number which represents the plenum/ambient pressure ratio for the simulation is $M_j = 1.19$ [9]. The computational domain, see Fig. 2(b), spans between

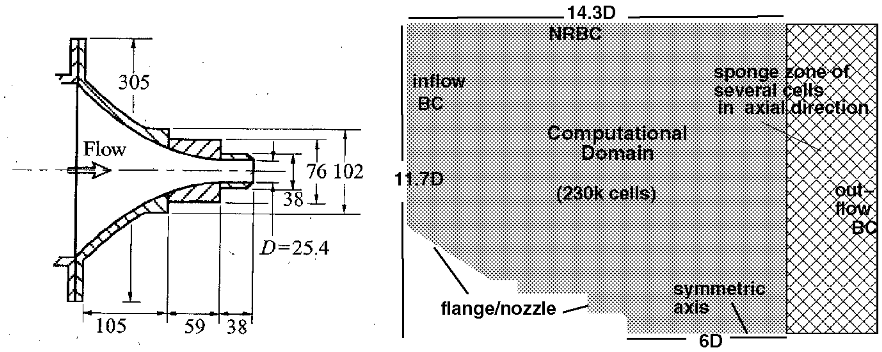
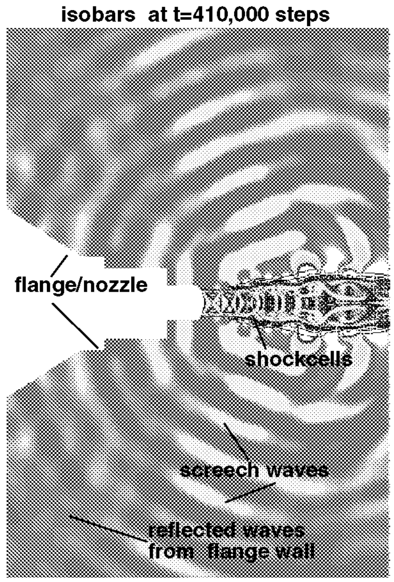



**Fig. 2.** (**a**) Geometry of the convergent nozzle and flange in Panda's experiment (dimensions in mm). (**b**) Computational domain

$-8.3D \leq x \leq 6D$ and $0 \leq r \leq 11.7D$, with x and r being the streamwise and radial coordinates and $D$ being the jet nozzle diameter. The flow inside the nozzle is not computed, rather the steady flow conditions are prescribed at the nozzle exit which is located at $x = 0$. This inflow plane is recessed by two cells so as not to numerically restrict or influence the feed-back loop. There are totally 230,000 triangle cells. Non-reflecting boundary conditions are applied to the upper and outflow boundaries and a symmetry condition is applied at the center axis. The last 10 streamwise cells have exponentially growing size and serve as a buffer, or sponge, zone to essentially eliminate any small remaining numerical reflection from the downstream outflow boundary. Initially, the entire flow is at rest and at ambient conditions; the jet flow is then impulsively started. The Reynolds number $Re = Da_o/\nu = 570,000$, where $a_o$ is the ambient speed of sound (used as velocity scale) and $\nu$ is the kinematic viscosity at the ambient conditions. Figure 3(a) displays numerical pressure contours and numerical Schlieren contours, outside and inside of the jet core respectively, well after the start-up transients has passed out of the computational domain. Distinct screech waves are observed to emit from the 3rd to the 5th shock-cell and are reflected at the flange/nozzle body. The screech wavelength ($1.6D$) and the shock-cell structure ($0.8D$ spacing) agree well with the experiment [9]; for the latter see Fig. 3(b). Spectral analysis yields a computed screech frequency of 8513 Hz, which agrees well with the experimental value of 8525 Hz. The sound pressure level (SPL) along an inclined line at the outer edge of the shear layer is shown in Fig. 4. This figure



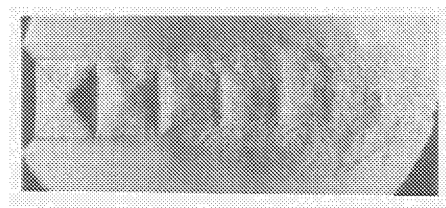



**Fig. 3.** (**a**) Isobars at t=410,000 steps, showing screech waves and shock cell structures. (**b**) Experimental Schlieren picture showing the shock-cell structure [9]

shows Panda's [9] data for the $A_2$ axisymmetric screech mode, the corresponding result from the simulation as well as the computed total SPL and subharmonic of the $A_2$ mode. Even though the $A_2$ SPL level in the vicinity of the nozzle lip is

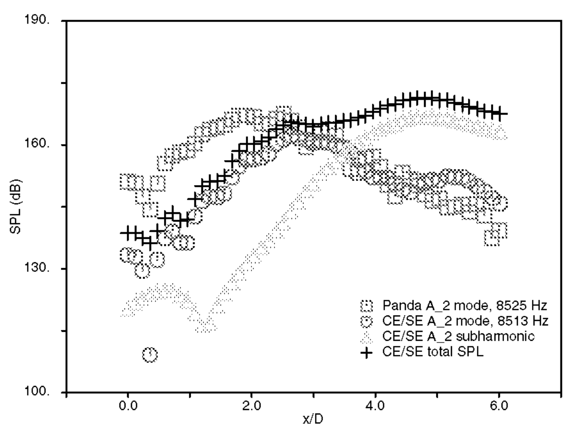



**Fig. 4.** Comparison of computed and experimental SPL along the shear layer edge

too low, its early streamwise growth rate is, however, well predicted indicating that the jet shear layer is in general well resolved. Nonlinearity in the shear layer limits the amplitude that can be obtained and once the SPL level 'catches up' the agreement is very good, in particular the SPL level in the streamwise region where the backward radiating acoustic waves are generated is well predicted. The strong subharmonic that appears further downstream is due to (axisymmetric) vortex pairing in the shear layer and as a consequence a second streamwise peak at the $A_2$ frequency occurs due to nonlinear effects. However, 3-D effects are most likely to have come into play in the experiment at these streamwise locations leading to suppression of the subharmonic. The reason for the low initial SPL values in the simulation is currently being pursued.

Figure 5 shows computed SPL contours for the $A_2$ mode. As in the experiment [9], a standing wave structure can be observed along the edge of the jet shear layer. The results are in general agreement with the experimental ones except, as pointed out earlier, that the computed SPL levels are too low in the vicinity of the nozzle lip and the existence of a second, or extended, region of elevated values further downstream ($x/D > 4$).

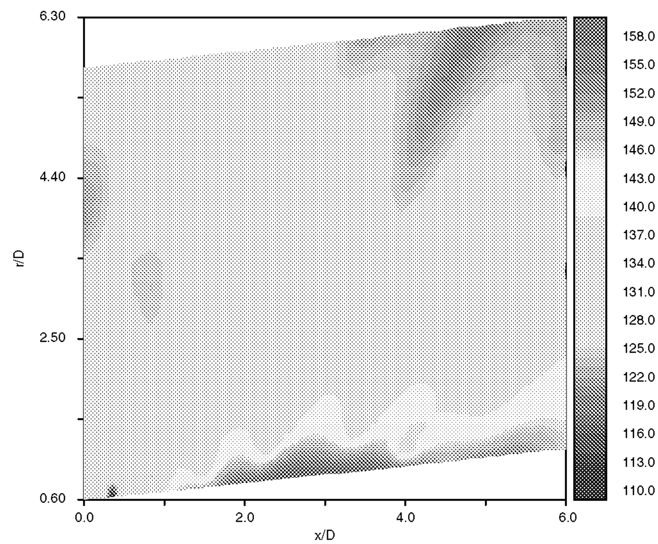



**Fig. 5.** Computed $A_2$-mode SPL levels for Panda's experiment

Figure 6 displays the computed SPL at the nozzle exit lip wall, $x/D = 0$, $r/D = 0.6$. The SPL shows a distinct spike corresponding to the $A_2$-mode screech tone observed in Panda's [9] experiment. Note that in our previous work [5], which had a much simplified description of the nozzle external geometry, the $A_1$-mode screech tone (not observed in [9]) was also obtained at this condition. This illustrates the sensitivity of the screech phenomenon to geometry changes.

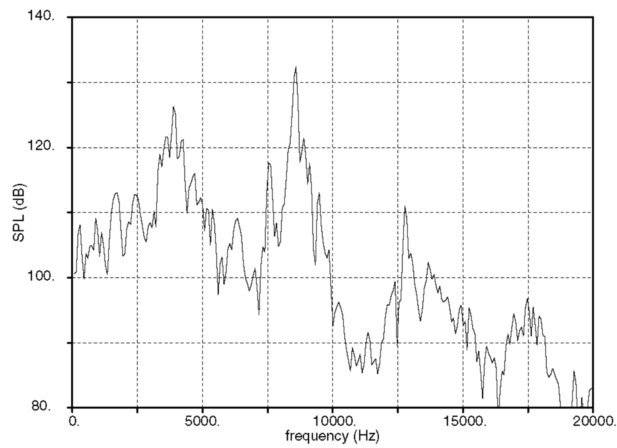



**Fig. 6.** SPL at nozzle exit ($x/D = 0$, $r/D = 0.6$), 75 Hz digital binwidth

## 4 Summary

It is concluded that the simulation shows a reasonably good agreement with experimental data in the streamwise region where the flow is expected to be predominantly axisymmetric and, hence, that jet screech is successfully simulated using the CE/SE scheme.

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