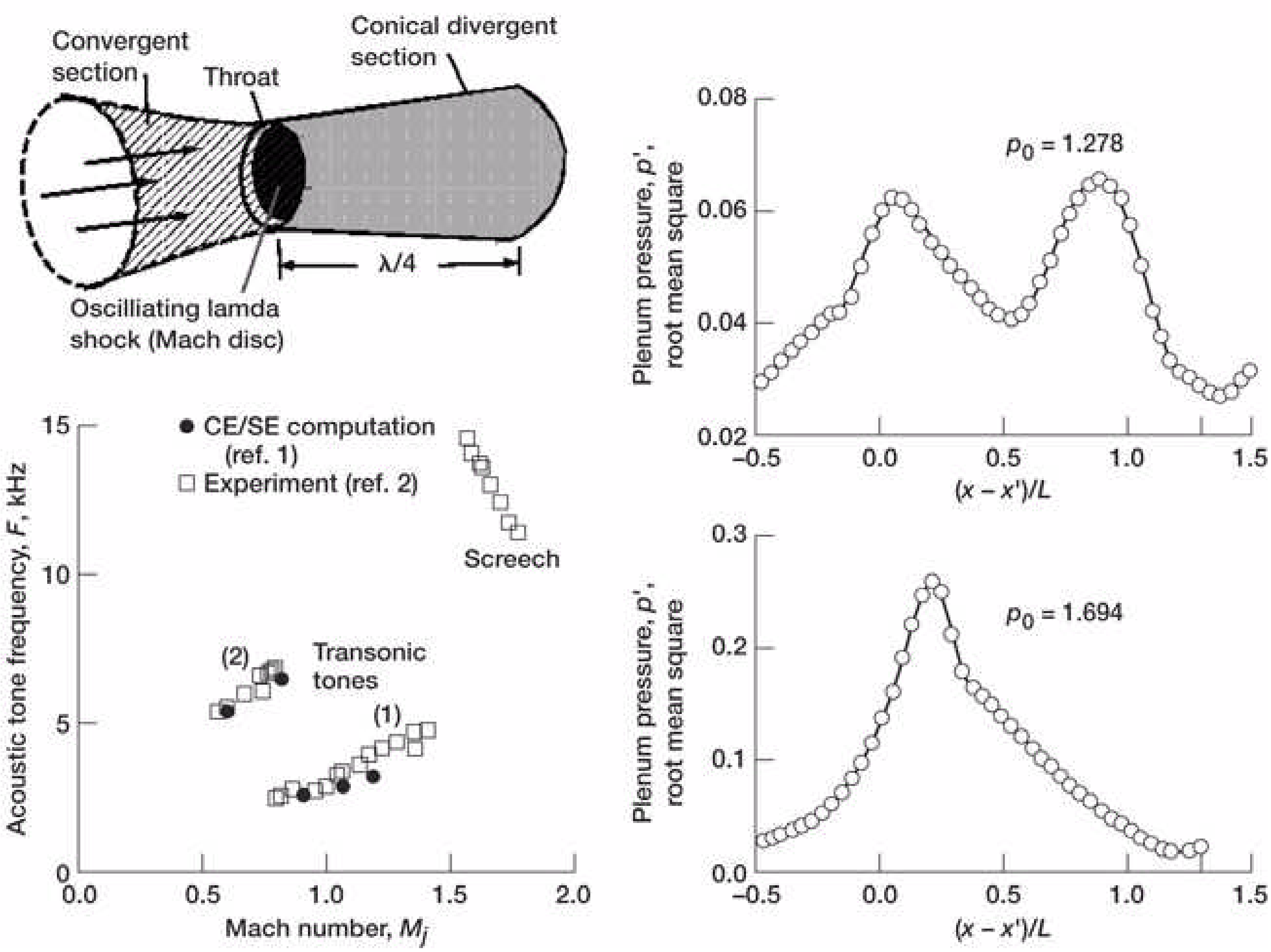
Aeroacoustic Flow Phenomena Accurately Captured by New Computational Fluid Dynamics Method

One of the challenges in the computational fluid dynamics area is the accurate calculation of aeroacoustic phenomena, especially in the presence of shock waves. One such phenomenon is "transonic resonance," where an unsteady shock wave at the throat of a convergent-divergent nozzle results in the emission of acoustic tones. The space-time Conservation-Element and Solution-Element (CE/SE) method developed at the NASA Glenn Research Center can faithfully capture the shock waves, their unsteady motion, and the generated acoustic tones.

The CE/SE method is a revolutionary new approach to the numerical modeling of physical phenomena where features with steep gradients (e.g., shock waves, phase transition, etc.) must coexist with those having weaker variations. The CE/SE method does not require the complex interpolation procedures (that allow for the possibility of a shock between grid cells) used by many other methods to transfer information between grid cells. These interpolation procedures can add too much numerical dissipation to the solution process. Thus, while shocks are resolved, weaker waves, such as acoustic waves, are washed out.

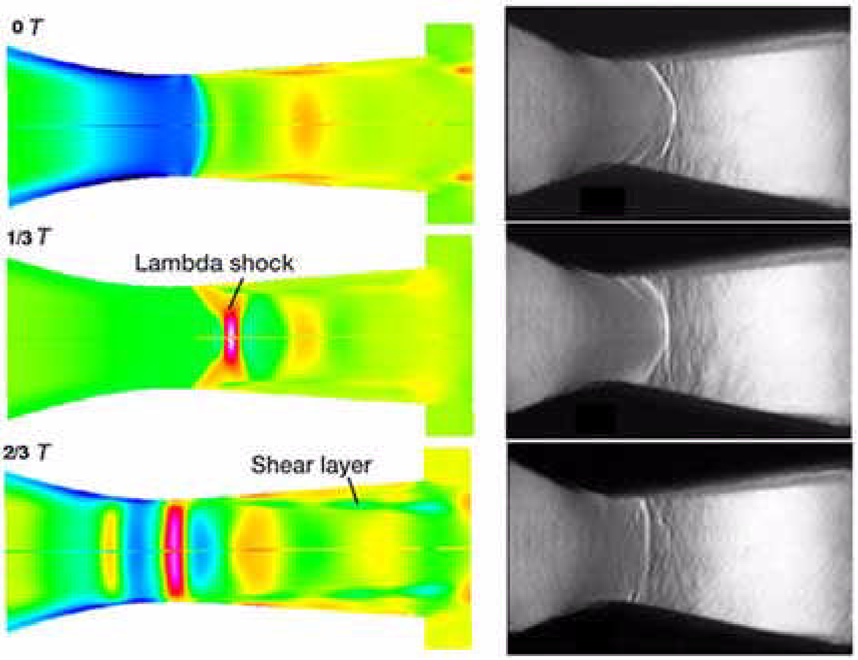


Upper left: Nozzle geometry. Lower left: Variation of tone frequency with jet Mach number. Right: Time-averaged (root mean square) amplitude of fluctuating pressure at two different plenum pressures.

Long description : Plot of acoustic resonance frequency versus Mach number. The experimental data taken by Zaman are plotted, as well as results calculated by Loh using the CE/SE method. The calculated results show excellent agreement with the experimental data. Both the variation of frequency with Mach number and the abrupt change in frequency at about Mach 0.8 are predicted. Also shown are plots of the root mean square pressure fluctuation amplitudes at the nozzle centerline in the axial direction. The top plot is for a plenum pressure p0 of 1.278, which results in a stage-2 tone. A three-quarter standing wave is established within the nozzle. The bottom plot is for a plenum pressure of 1.694. Here, a one-quarter standing wave is set up, resulting in an abrupt shift in frequency

In the preceding figure, nozzle geometry is shown in the upper left quadrant. The convergent-divergent nozzle has diameters of 1.5, 0.3, and 0.4 in. at the inlet, throat, and exit, respectively. The throat is located 2.0-in. downstream of the inlet. The inlet is connected to a plenum with a static pressure p_0 of 1.694 psi. The lower left quadrant shows the acoustic tone frequency plotted as a function of the jet Mach number, M_j. The filled circles represent frequencies computed using a two-dimensional axisymmetric code based on the CE/SE method. The open squares represent experimental data by Zaman (ref. 1). Note that the plot shows data for both transonic tones and screech. Screech tones occur at higher jet Mach numbers. The transonic tones are of interest here. From the figure, it is evident that the results calculated by the CE/SE method show excellent agreement with the experimental data. The frequency shift with M_j, known as "staging," is captured accurately as well.

On the right side of the figure are two plots of the root mean square pressure fluctuation amplitudes at the nozzle centerline in the axial direction. The top plot is for a plenum pressure, $p_0 = 1.278$, which results in a stage-2 tone. It can be seen that a three-quarter standing wave is established within the nozzle. The following plot is for a plenum pressure of 1.694. Here, a one-quarter standing wave is set up, resulting in an abrupt shift in frequency. The figure to the left (following figure) shows the CE/SE method's excellent shock-capturing capability. Note the resolution of the lambda shock in the middle frame. The experimental schlieren data (figure to the right) are taken from the experiments of C.A. Hunter at the NASA Langley Research Center (ref. 2).



Comparison of shock structures for CE/SE computations and a similar experiment by Hunter. T represents one period of the transonic resonance oscillation.

Long description : CE/SE method’s excellent shock capturing capability. Left: Numerical schlieren results from CE/SE computations. Right: Experimental schlieren data. The top part of the figure shows a bow-shaped shock, and in the middle frame a lambda shock is clearly seen in both the experiment and the computation.

The CE method is also being applied in two-dimensional axisymmetric codes to jet screech noise, turbomachinery noise, and pulse detonation engines. In all cases, excellent results have been obtained. A three-dimensional code based on CE/SE is currently being evaluated.

Find out more about this research http://www.grc.nasa.gov/WWW/microbus/.

References

1. Loh, C.Y. and Zaman, K.B.M.Q.: Numerical Investigation of 'Transonic Resonance' With a Convergent-Divergent Nozzle. AIAA Paper 2002-0077, 2002.
2. Zaman, K.B.M.Q.; Dahl, M.D.; and Bencic, T.J.: Experimental Investigation of 'Transonic Resonance' With Convergent-Divergent Nozzles. AIAA Paper 2001-0078, 2001.
3. Hunter, Craig A.: Experimental, Theoretical, and Computational Investigation of Separated Nozzle Flows. AIAA Paper 98-3107, 1998.

Bibliography

Chang, Sin-Chung: The Method of Space-Time Conservation Element and Solution ElementA New Approach for Solving the Navier-Stokes and Euler Equations.
J. Comput. Phys., vol. 119, 1995, pp. 295-324.

Chang, Sin-Chung.; Wang, Xiao-Yen.; and Chow, Chuen-Yen: The Space-Time Conservation Element and Solution Element Method: A New High-Resolution and Genuinely Multidimensional Paradigm for Solving Conservation Laws. J. Comput. Phys., vol. 156, 1999, p. 89-136.

Loh, Ching-Y.; Hultgren, Lennart S.; and Chang, Sin-Chung: Wave Computation in Compressible Flow Using the Space-Time Conservation Element and Solution Element Method. AIAA J., vol. 39, no. 5, 2001, pp. 794-801.

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