DIRECT NUMERICAL SIMULATION OF PRESSURE FLUCTUATIONS INDUCED BY SUPERSONIC TURBULENT BOUNDARY LAYERS

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PI: Lian Duan[1]
Collaborator: Meelan Choudhari[2]

[1]Missouri University of Science and Technology
[2]NASA Langley Research Center

EXECUTIVE SUMMARY

When air flows over solid surfaces at high speeds, the very thin region near the surface that is referred to as the boundary layer can become chaotic and turbulent; these turbulent motions can then generate intense, outward-propagating sound waves. In particular, for fast flows inside a supersonic wind tunnel, the turbulent boundary layer over the tunnel wall radiates outward-propagating sound waves and causes the generation of freestream acoustic noise in the wind tunnel. This research exploited the cutting-edge computational power of the Blue Waters to advance fundamental understanding of the generic statistical and spectral features of acoustic radiation from high-speed turbulent boundary layers. Such an understanding helps define the freestream disturbances environment in supersonic/hypersonic wind tunnels and allows more accurate extrapolation of experimental measurements from noisy wind tunnels to free flight.

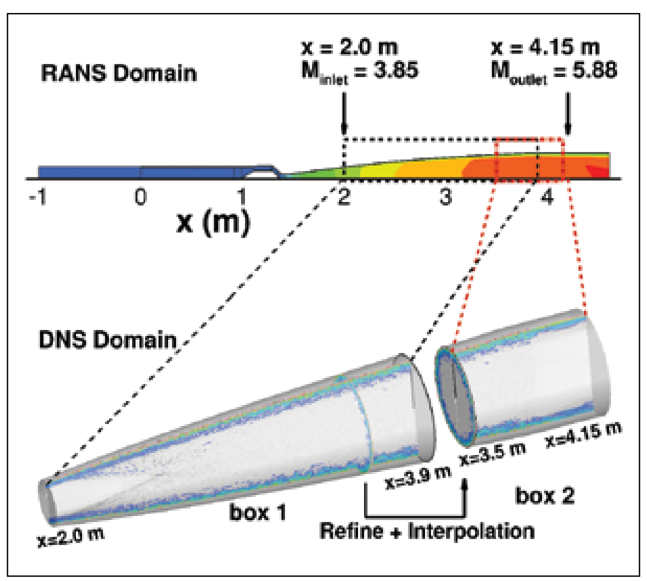

Figure 1: Hypersonic Ludwieg Tube at the Technical University of Braunschweig. The DNS domain covers the origin of most of the acoustic sources responsible for generating freestream noise in the test section.

RESEARCH CHALLENGE

Testing in conventional (noisy) wind tunnels has been an important means of characterizing and understanding when, where, and how a high-speed boundary layer flowing over an aerodynamic body transitions to turbulence, which causes a large increase in skin-friction drag and surface heating. Because the existing low-disturbance (*i.e.*, quiet) facilities operate only at Mach 6, moderate Reynolds numbers (the ratio of inertial forces to viscous forces within a fluid), fairly small sizes, and low freestream enthalpy (total heat content of a system), conventional facilities will continue to be employed for testing and evaluation of high-speed vehicles, especially for ground testing involving other Mach numbers, higher freestream enthalpies, and larger models. To enable better use of transition data from conventional facilities and more accurate extrapolation of wind tunnel results to flight, one needs an in-depth knowledge of the broadband disturbance environment in those facilities, which is dominated by acoustic radiation from tunnel wall turbulent boundary layers.

METHODS & CODES

Direct numerical simulations (DNS) were conducted using HyperWENO, an in-house high-order finite-difference solver that solves the compressible Navier–Stokes equations describing the evolution of the density, momentum, and total energy of the flow. The governing equations can be described and solved in either general curvilinear coordinates or cylindrical coordinates, depending on the flow configuration. The inviscid fluxes of the governing equations were computed using a seventh-order weighted essentially nonoscillatory (WENO) scheme. Compared with the original finite-difference WENO introduced by Jiang and Shu [1], the present scheme is optimized by means of limiters [2] to reduce the numerical dissipation; WENO adaptation was limited to the boundary-layer region for maintaining numerical stability while the optimal stencil of WENO was used outside the boundary layer for optimal resolution of the radiated acoustic field. A fourth-order central difference scheme was used for the viscous flux terms, and a third-order low-storage Runge–Kutta scheme [3] was employed for time integration, which significantly relieved the memory requirement and is well suited for time-accurate simulations such as DNS. The turbulent inflow can be generated using either a recycling/rescaling method [4] or a digital filtering method [5]. On the wall, no-slip conditions were applied for the three velocity components and an isothermal condition was used for the temperature. At the top and outlet boundaries, unsteady nonreflecting boundary conditions were imposed. Periodic boundary conditions were used in the spanwise or azimuthal direction.

RESULTS & IMPACT

The current work advanced the state-of-the-art knowledge of the global pressure field induced by supersonic turbulent boundary layers across a wide range of Mach numbers. The study represents the first-ever attempt to exploit the advances in high-performance computing to overcome the difficulties in experimental measurements and to provide access to both flow and acoustic quantities that are difficult to obtain otherwise. In particular, the study led to an unprecedented simulation of a full-scale nozzle of a hypersonic wind tunnel (Fig. 1) and allowed the first successful comparison between numerical predictions and measurements of pressure fluctuations over the nozzle wall. The simulations also captured all major features of the freestream disturbance spectra and structures (Fig. 2) and helped clarify the physics of the noise generation process in supersonic/hypersonic wind tunnels. The characterization of wind tunnel freestream disturbances paved the way for extrapolation to flight from the boundary-layer transition data obtained in noisy wind tunnels.

WHY BLUE WATERS

DNS are used to capture both the broadband turbulence field within the boundary layer and the near-field acoustic disturbances radiated by the boundary layer. In such simulations, extremely fine meshes are required to fully resolve all the turbulence scales in order to obtain the pressure spectra in the high-frequency/large-wave-number range. In the meantime, the simulations need large domain sizes to locate very-large-scale coherent structures in the pressure field as well as to accommodate the eddy decorrelation length and to minimize inlet transience as a result of inflow boundary conditions. A large number of timesteps are also required for the study of the low-frequency behavior of the pressure spectrum. As such, the proposed computational efforts cannot be conducted without the world-class computing capabilities of Blue Waters.

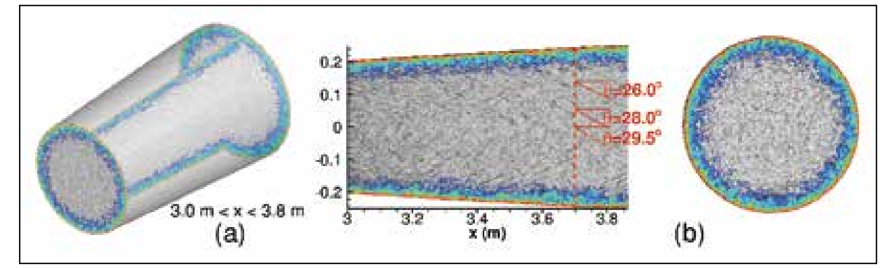

Figure 2: Numerical schlieren images (*i.e.*, density gradient contours) of radiated acoustic waves within the nozzle of the Hypersonic Ludwieg Tube. The vertical dashed line indicates the axial location of the selected cross-section visualized in the right panel of (b).

PUBLICATIONS & DATA SETS

L. Duan *et al.*, "Characterization of freestream disturbances in conventional hypersonic wind tunnels," *J. Spacecraft and Rockets*, vol. 56, no. 2, pp. 357–368, 2019, doi: 10.2514/1.A34290.

C. Zhang, L. Duan, and M. M. Choudhari, "Direct numerical simulation database for supersonic and hypersonic turbulent boundary layers," *AIAA J.*, vol. 56, no. 11, pp. 4297–4311, 2018, doi: 10.2514/1.J057296.

"DNS: Supersonic/hypersonic zero-pressure-gradient plate flows," webpage in *NASA Langley Turbulence Modeling Resource*, Nov. 2018. [Online]. Available: https://turbmodels.larc.nasa.gov/Other_DNS_Data/supersonic_hypersonic_flatplate.html