PRESSURE FLUCTUATIONS INDUCED BY SUPERSONIC TURBULENT BOUNDARY LAYERS

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EXECUTIVE SUMMARY

The fluctuating pressure on aerodynamic surfaces of flight vehicles plays an important role in vibrational loading during atmospheric reentry; the freestream pressure fluctuations radiated from a supersonic boundary layer is related to the genesis of freestream acoustic noise by walls of a supersonic wind tunnel. This research exploited the cutting-edge computational power of Blue Waters to advance fundamental understanding of the generic statistical and spectral features of boundary-layer-induced pressure fluctuations at the wall and in the freestream. Such an understanding paves the way for developing physics-based models to predict vibratory loading of reentry vehicles, as well as to help define the disturbances caused by the tunnel walls in supersonic/hypersonic wind tunnels and allow more accurate extrapolations of wind-tunnel measurements to free flight.

RESEARCH CHALLENGE

Understanding the physics of the pressure fluctuations induced by turbulent boundary layers is of major theoretical and practical importance. From a practical point of view, the fluctuating pressure on aerodynamic surfaces of flight vehicles plays an important role in vibrational loading and often leads to damaging effects such as fatigue and flutter. The freestream pressure fluctuations radiated from the turbulent boundary layer on the nozzle wall is responsible for the genesis of freestream acoustic noise in supersonic wind tunnels. Therefore, the characterization of tunnel acoustic noise is critically important to experimental measurement of boundary-layer transition in such wind tunnels. From a theoretical point of view, pressure is of fundamental importance to understanding the turbulent vorticity dynamics, and to modeling the pressure-strain terms in the Reynolds stress closure.

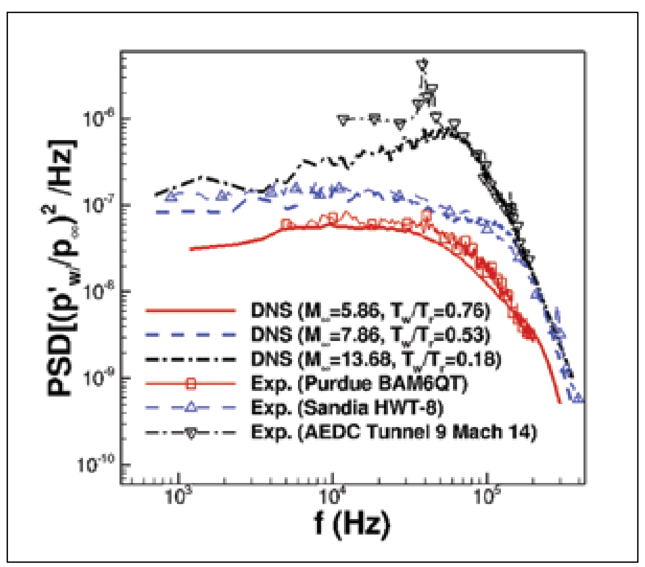

Figure 1: Comparison between numerical predictions and wind tunnel measurements of surface pressure fluctuations underneath a hypersonic turbulent boundary layer, with the experimental data measured on the nozzle walls of the Purdue Boeing/AFOSR Mach-6 Quiet Tunnel, the Sandia Hypersonic Wind Tunnel at Mach 8, and AEDC Tunnel 9.

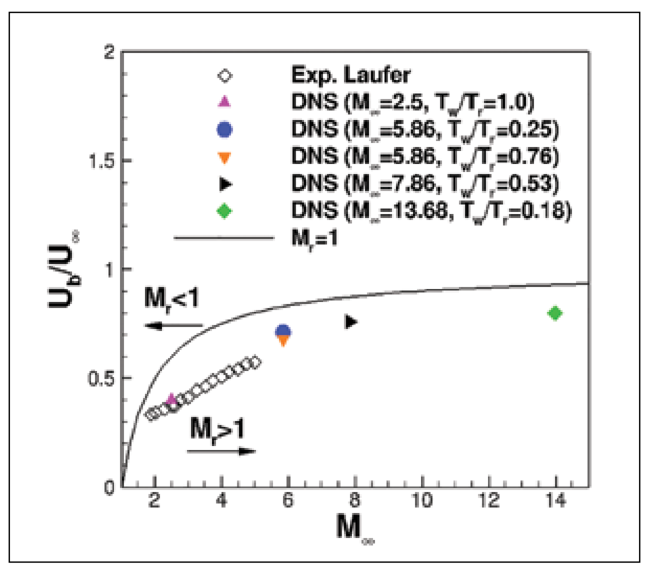

Figure 2: Comparison between numerical predictions and wind tunnel measurements of bulk propagation speed of the freestream acoustic pressure fluctuations radiated from a supersonic turbulent boundary layer, with the experimental data measured during a one-of-a-kind, historical wind tunnel campaign by Laufer [6].

METHODS & CODES

We conducted Direct Numerical Simulations (DNS) using HyperWENO, an in-house high-order finite-difference solver that solves the compressible Navier–Stokes equations in generalized curvilinear coordinates describing the evolution of the density, momentum, and total energy of the flow. The very-low viscosity fluxes of the governing equations are computed using a seventh-order weighted essentially nonoscillatory (WENO) scheme. Compared to 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 is limited to the boundary-layer region for maintaining numerical stability while the optimal stencil of WENO is used outside the boundary layer for optimal resolution of the radiated acoustic field. A fourth-order central difference scheme is used for the viscous flux terms, and a third-order low-storage Runge–Kutta scheme [3] is employed for time integration, which significantly lowers the memory requirement and is well-suited for time-accurate simulations like 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 are applied for the three velocity components, and an isothermal condition is used for the temperature. At the top and outlet boundaries, unsteady nonreflecting boundary conditions are imposed. Periodic boundary conditions are used in the spanwise (wing tip to wing tip) 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 trailblazing 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 otherwise obtain. In particular, the study led to the first successful comparison between numerical predictions and wind tunnel measurements of surface pressure fluctuations underneath hypersonic turbulent boundary layers at Mach 6, 8, and 14 (Fig. 1). The simulations also captured all major features of the freestream disturbance spectra that had been measured during a one-of-a-kind, historical wind tunnel campaign [6] (Fig. 2), helping to 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

Direct numerical simulations 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 transient as a result of inflow boundary conditions. A large number of timesteps are also required for the study of low-frequency behavior of the pressure spectrum. As such, the proposed computational efforts cannot be completed without the world-class computing capabilities of Blue Waters.

PUBLICATIONS & DATA SETS

Duan, L., et al., Characterization of Freestream Disturbances in Conventional Hypersonic Wind Tunnels. *2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum*, AIAA Paper 2018–0347, DOI:0.2514/6.2018-0347.

Huang, J., et al., High-Mach-Number Turbulence Modeling using Machine Learning and Direct Numerical Simulation Database, AIAA Paper 2017–0315, *55th AIAA Aerospace Sciences Meeting*, DOI:10.2514/6.2017-0315.