DNS OF PRESSURE FLUCTUATIONS INDUCED BY SUPERSONIC TURBULENT BOUNDARY LAYERS

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EXECUTIVE SUMMARY

Pressure fluctuations are an important ingredient in wall-bounded turbulence as they are strongly correlated with turbulent vorticity dynamics and noise generation. Most existing analyses of boundary-layer-induced pressure fluctuations are based on the Poisson equation in the context of incompressible boundary layers. The pressure fluctuations induced by a supersonic turbulent boundary layer are, however, governed by the wave equation and are fundamentally more complicated than the low-speed counterpart. The objective of the research is to conduct direct numerical simulations (DNS) to advance fundamental understanding of the generic statistical and spectral features of boundary-layer-induced pressure fluctuations, including the freestream acoustic radiation at supersonic speeds and their dependence on boundary-layer parameters such as the Reynolds number. Current work with Blue Waters includes the analysis of boundary-layer data at modest Reynolds numbers, and conducting new simulations in Reynolds-number regimes difficult to reach without the large allocation provided on Blue Waters.

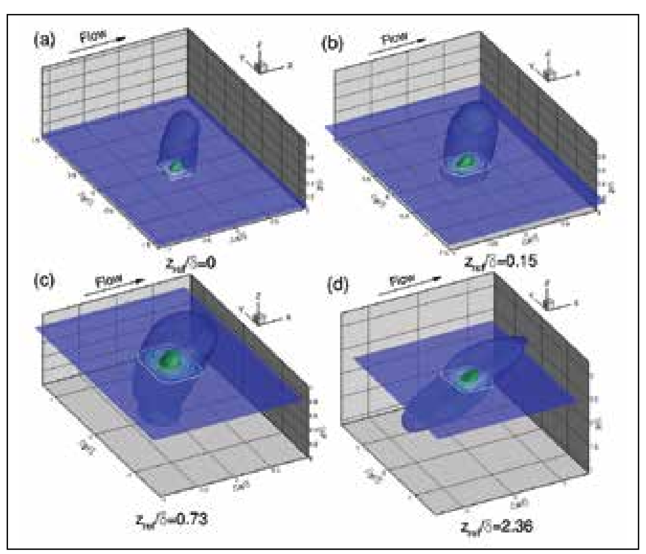

Figure 1: Three-dimensional representation of the spatial correlation coefficient of the pressure signal at multiple wall-normal locations for a Mach 6 cold-wall turbulent boundary layer at $Re_\tau \approx 450$. z_{ref}/δ denotes the wall-normal location of the correlation origin normalized by the boundary layer thickness and three-dimensional isosurfaces are shown at 0.1 (blue) and 0.6 (green). In the horizontal planes going through the correlation origin, the contour lines shown in white range from 0.1 to 0.9.

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 are 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 stability and 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.

One unique feature of boundary-layer-induced pressure fluctuations at supersonic speeds is that acoustic mode fluctuations emerge in the form of eddy Mach waves [1]. The pressure fluctuations thus include contributions from both vortical and acoustic modes. The characteristics of the acoustic pressure fluctuations and the relative importance of the two modes in different regions of the boundary layer are largely unknown. The current work aims to use the cutting-edge computational power of Blue Waters to provide the basis for an in-depth understanding of the global pressure field induced by supersonic turbulent boundary layers across a wide range of boundary-layer parameters. Such an understanding will advance the state-of-the-art knowledge of wall-bounded turbulence and boundary-layer-induced noise.

METHODS & CODES

DNS are conducted 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. An optimized, high-order (up to 7th order) finite-difference WENO (weighted essentially non-oscillatory) scheme [2,3] is used to compute the convective flux. The WENO scheme combines a high order of accuracy with relatively low dissipation, making it suitable for simulations of compressible turbulent flows. A 4th-order central difference scheme is used for the viscous flux terms, and a 3rd-order low-storage Runge-Kutta scheme [4]

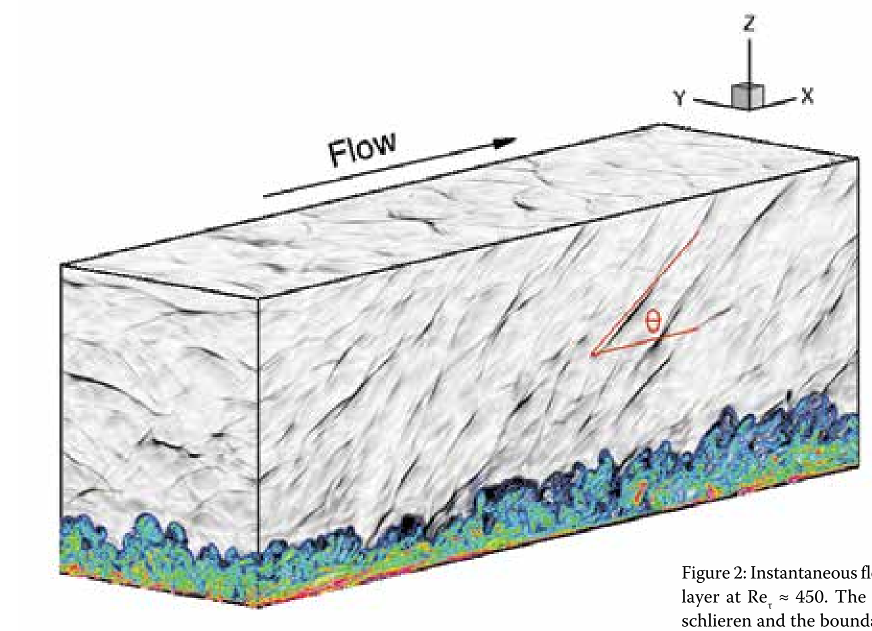

Figure 2: Instantaneous flow visualization for a Mach 6 cold-wall turbulent boundary layer at $Re_\tau \approx 450$. The freestream acoustic noise is visualized using numerical schlieren and the boundary layer is colored by the vorticity magnitude. The angle θ illustrates the preferred direction of radiated acoustic wavefront.

is employed for time integration, which significantly relieves 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 [5] or a digital filtering method [6]. 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 direction.

RESULTS & IMPACT

We have used the computational resources of Blue Waters to investigate the characteristics of pressure fluctuations generated by nonadiabatic cold-wall turbulent boundary layers with a nominal Mach number of 6 and a Karman Reynolds number of $Re_\tau \approx 450$; results were published in the *Journal of Fluid Mechanics*. The DNS have overcome a number of difficulties encountered during experimental measurements of broadband pressure fluctuations and have provided access to quantities that cannot be measured easily, including multi-variate pressure statistics and large-scale structures in the pressure field (Figs. 1, 2). By comparing turbulent boundary layers with different wall-cooling rates, the study provides, for the first time, fundamental understanding of the effect of wall cooling on the global pressure field.

In the near term, we would like to perform DNS of supersonic turbulent boundary layers at a significantly higher Karman Reynolds number ($Re_\tau > 2{,}000$) to study the dependence of the global pressure field on the Reynolds number. Significant progress has been made to re-engineer HyperWENO to overcome I/O bottlenecks and improve node-level parallelism with guidance from the Blue Waters support team. Test runs to date performed with the re-engineered DNS code have shown encouraging computation and I/O performance.

WHY BLUE WATERS

Direct numerical simulations of high-Reynolds-number turbulent boundary layers will be used to study the broadband fluctuating pressure field induced by the boundary layer, with the targeted Reynolds numbers significantly higher than the state of the art. 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 time steps are also required for the study of the low-frequency behavior of the pressure spectrum. As such, the proposed computational efforts cannot be done without the world-class computing capabilities of Blue Waters.

PUBLICATIONS AND DATA SETS

Zhang, C., L. Duan, and M. M. Choudhari, Effect of wall cooling on boundary-layer-induced pressure fluctuations at Mach 6, *Journal of Fluid Mechanics*, 822 (2017), pp. 5–30.