HIGH-END VISUALIZATION OF COHERENT STRUCTURES AND TURBULENT EVENTS IN WALL-BOUNDED FLOWS WITH A PASSIVE SCALAR

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EXECUTIVE SUMMARY

Despite the chaotic behavior of turbulence, investigations performed during the last six decades have conclusively demonstrated the presence of organized motions called "coherent structures" in turbulent boundary layers, which are responsible for transporting most of the turbulent kinetic energy. Investigations have also elucidated passive scalars, which are defined as diffusive contaminants that exist in a low concentration but sufficiently enough to provoke a significant impact on energy expenditures, heat transfer, and air pollution. Research has also found that the transport phenomenon in real-situation flows usually occurs under complicated external conditions such as favorable/adverse pressure gradients, local flow perturbations, and spatially developing boundary layers. Therefore, computational investigation through Direct Numerical Simulation (DNS) with millions of "flow and thermal sensors" and high temporal resolution may shed light on the unknown aspects of transport phenomena in accelerated/decelerated boundary layers. In addition, coherent structures in such a complex environment and their interactions (turbulent events) can be better identified and visualized by DNS.

RESEARCH CHALLENGE

These research efforts make use of tremendous computational resources, not only during the running stage but also in the visualization–animation stage. Therefore, state-of-the-art parallel computing and graphics processing unit (GPU) programming are essential. Furthermore, the high spatial/temporal resolution of DNS examines the physics behind turbulent events and passive scalar transport in highly accelerated/decelerated boundary layers for potential applications to flow/heat transfer control and turbulence modeling in aerospace applications.

The research team's DNS study uses thousands of cores in a parallel computational environment. DNS is a numerical tool that aims to resolve all turbulent length and time scales, capturing the whole energy spectrum of the flow field. Consequently, the numerical approach requires high mesh resolution and, thus, very small physical timesteps or high temporal resolution. This results in highly costly numerical predictions with the payoff of getting the whole "picture" of the problem: no other numerical approach can supply such a level of information and accuracy in turbulent wall-bounded flows. Even experimental approaches fail to measure transport phenomena in the near-wall region of boundary layers. DNS is able to accurately predict flow parameters in regions up to one hundred times closer to the surface than in experiments. Traditionally, DNS has been limited to small computational domains (or low Reynolds numbers); however, the significant growth of petascale computing resources such as Blue Waters has allowed researchers to tackle higher Reynolds number problems in a reasonable time. To the best of the researchers' knowledge, this project is the first time that numerical predictions of high-Reynolds-number boundary layers subject to extreme streamwise pressure gradients have been carried out, representing a formidable computational challenge with tremendous importance for the fluid dynamics and scientific visualization communities.

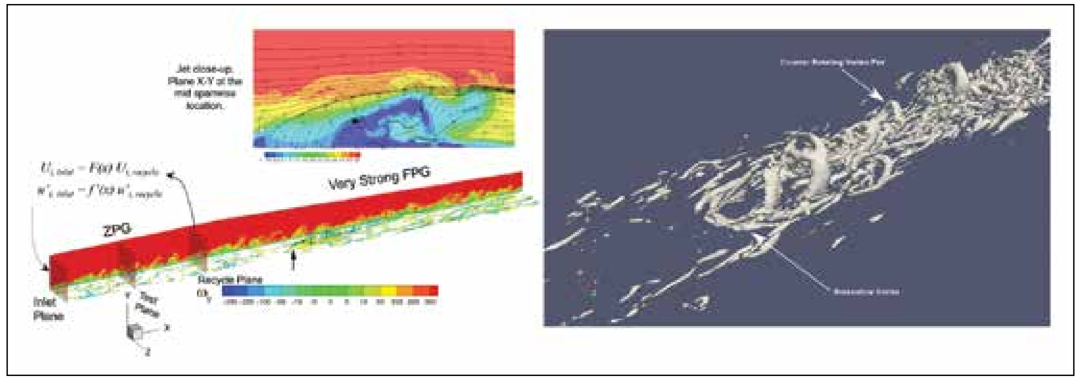

Figure 1: (left) Schematic of the spatially developing boundary layer in FPG flows with Inlet, Recycle, and Test planes. (right) Vortical structures emanating from the crossflow jet system.

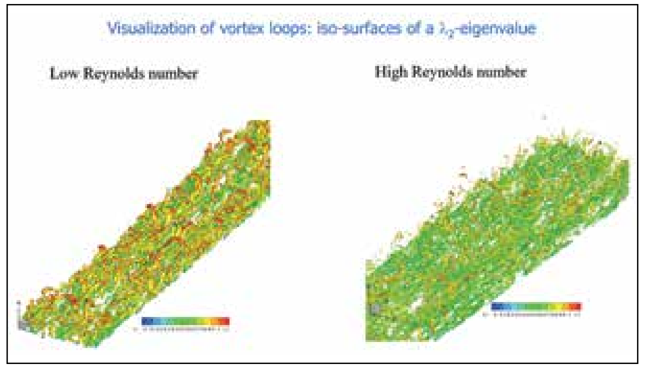

Figure 2: Iso-contours of a λ_2 eigenvalue in low and high Reynolds numbers of zero-pressure gradient flows.

METHODS & CODES

Computationally speaking, it is very challenging to capture the physics of unsteady spatially developing turbulent boundary layers owing to the following requirements: (1) the high resolution necessary to resolve the small scales, (2) a computational box that is large enough to appropriately capture the influence of the large-scale motions, and (3) the realistic time-dependent inflow turbulent conditions that must be prescribed. Therefore, the research team used the inflow generation method devised by Araya *et al.* [1], which is an improvement on the original rescaling–recycling method of Lund *et al.* [2]. The seminal idea of the rescaling/recycling method is to extract the flow solution (mean and fluctuating components of the velocity and thermal field) from a downstream plane (called "recycle") and after performing a transformation by means of scaling functions, the transformed profiles are reinjected at the inlet plane, as seen in Fig. 1.

To successfully perform the DNS, a highly accurate, efficient, and highly scalable computational fluid dynamics solver is required. PHASTA is an open-source, parallel, hierarchic (second- to fifth-order accurate), adaptive, stabilized (finite-element) transient analysis tool for the solution of compressible [3] or incompressible flows [4]. Combining minimal dissipation numerics and adaptive unstructured meshes, PHASTA has been applied to flows ranging from validation on DNS and large-eddy simulation benchmarks such as channel flow and decay of isotropic turbulence to cases of practical interest including incompressible and compressible boundary-layer flow control. PHASTA has been carefully constructed for parallel performance and scaling to 786,432 cores (on one, two, and four processes per core, which exceeds three million processes) in Mira (Argonne's 10 petaflop supercomputer). PHASTA has also been ported and scaled well on GPU-based and Intel® Xeon Phi™-based-based machines.

RESULTS & IMPACT

This project, based on DNS big data, contributed to a better understanding of coherent structures, turbulent events, and passive scalar transport in boundary layers subject to streamwise pressure gradients and vertical jets, and pushed the boundaries in terms of high-end visualization. It has also led to the improvement of flow control tools for mixing enhancement, drag reduction, and heat-transfer augmentation in aerospace applications such as the film cooling technique. Fig. 1 depicts iso-contours of the Q-criterion [5] in order to visualize coherent structures emanating from the crossflow jet. It has been observed that the counter-rotating vortex pair system experienced a quick attenuation owing to the strong flow acceleration prescribed (Favorable Pressure Gradient). Furthermore, DNS of high Reynolds number zero-pressure gradient flows has been performed in large-scale systems (approximately 52 million grid points). Fig. 2 shows iso-contours of a λ_2 eigenvalue for coherent structure visualization in low and high Reynolds number flows. The presence of vortex loops in low Reynolds number flows (horseshoes) is evident, while the turbulence structure seems finer and more isotropic in high Reynolds number flows (hairpins). Since the lead institution of this project is the University of Puerto Rico at Mayaguez, the research impact has involved underrepresented minorities: six undergraduate students, two graduate students, and one early-career faculty.

WHY BLUE WATERS

This project makes use of state-of-the art DNS, which supplies the highest possible level of flow information but at a high computational cost. This endeavor would not be possible without the invaluable contribution and support of the Blue Waters resources.

PUBLICATIONS & DATA SETS

G. Araya, G. Marin, F. Cucchietti, I. Meta, and R. Grima, "Visualization of a jet in turbulent crossflow," in *High Performance Computing, 5th Latin American Conference*, Bucaramanga, Colombia, Sept. 27, 2018, pp. 174–178, doi: 10.1007/978-3-030-16205-4_13.

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G. Saltar and G. Araya, "Turbulence modeling of boundary layers subject to very strong Favorable Pressure Gradient (FPG) with passive scalar transport," in *Proc. 4th Thermal and Fluids Engineering Conf.*, Las Vegas, NV, U.S.A., Apr. 15, 2019, pp. 1819–1833, doi: 10.1615/TFEC2019.tfl.028426.

J. Santiago, G. Araya, G. Marin, and F. Cucchietti, "Symbiosis of quasi-streamwise vortices and low-speed streaks in laminarescent boundary layers," presented at the 71th Annual Meeting of the American Physical Society—Division of Fluid Dynamics, Atlanta, GA, U.S.A., November 18–20, 2018.

G. Saltar and G. Araya, "Coherent structure assessment in crossflow jets subject to strong favorable pressure gradient (FPG)," presented at the 71th Annual Meeting of the American Physical Society—Division of Fluid Dynamics, Atlanta, GA, U.S.A., November 18–20, 2018.