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Kinetic Treatment of High-Speed Flows: Stability and Transition Mechanisms

SPEAKER

Irmak Taylan Karpuzcu, PhD Candidate, Department of Aerospace Engineering
University of Illinois at Urbana-Champaign, IL, USA

ABSTRACT

This talk explores the gas dynamics of high-speed flows over two-dimensional compression ramps at high altitudes. Compression ramps are common features of vehicles traveling at supersonic and hypersonic speeds and are encountered, e.g., at engine inlets, fin junctions and control surfaces on which complex supersonic flows with several shocks, shear layers and recirculation zones are created. The main goal is to investigate the formation and stability of large separation bubbles whose extent nearly covers the flat plate and interacts strongly with the shock system of the compression ramp. Since these flow features can trigger transition to turbulence, understanding the underlying instability mechanisms is critical. Turbulence increases heat transfer rates and introduces unsteadiness, both of which have important implications for vehicle control, structural integrity, and thermal management. Large separation regions enabled the detailed investigation of the stability of the single recirculation in the separation region, that is characterized by the appearance of the secondary recirculation and unsteadiness in two dimensional simulations as well as growth of three-dimensional disturbances. Particle-kinetic Direct Simulation Monte Carlo (DSMC), data driven methods and continuum-based Linear Stability Theory Analysis (LSTA) are employed in this work leveraging on the high-performance computing software. DSMC is particularly effective at capturing non-equilibrium effects and the detailed inner structure of shock layers. Two-dimensional and three-dimensional DSMC simulations are performed under low-Knudsen-number conditions for several ramp configurations, ensuring that the continuum assumption largely holds yet still capturing non-equilibrium effects inside the shock layers. The configurations where the flows are observed to be unsteady in two-dimensional simulations, spectral proper orthogonal decomposition analysis revealed low frequency unsteadiness and main sources of unsteadiness were observed as the oscillations of the reattachment shock, Kelvin-Helmholtz instability of the shear layer and the c-shaped mode of the separation bubble. A BiGlobal linear stability analysis is applied to the two-dimensional, steady flow fields and a previously unknown traveling global mode discovered in the largest ramp angle configuration, with amplitude functions that peak within and around the leading-edge shock and along the shear layer. Once nonlinear effects become significant after the growth of these unstable three-dimensional perturbations, streamwise-aligned vortices form in the recirculation region, and Λ-vortices appear shortly downstream of reattachment, hallmarks of a transitional process. Overall, this talk presents a detailed characterization of high-speed flow behavior over a canonical geometry using high-fidelity numerical methods and highlights new physical insights revealed by computational analysis.

ABOUT THE SPEAKER

Irmak Taylan Karpuzcu is a PhD candidate in the Department of Aerospace Engineering at the University of Illinois at Urbana-Champaign, working under the supervision of Prof. Deborah Levin. He earned his Master of Science degree in Mechanical Engineering (2019) and his Bachelor of Science degree (2015) from Middle East Technical University, where he conducted his graduate research under the supervision of Prof. Cüneyt Sert. He is a certified graduate teacher and a MAVIS future faculty fellow. His research focuses on the numerical simulation of high-speed fluid flows, leveraging high-performance computing techniques. His master's work centered on modeling turbulence in supersonic flows using large eddy simulation. His initial PhD research focused on the non-equilibrium thermochemistry of hypersonic flows. Currently, his research involves investigating the stability of high-speed laminar flows at high altitudes using kinetic theory, linear stability analysis, and data-driven approaches.

CONTACT

Dr. Orçun Koray Çelebi, Mechanical Engineering Department, Bilkent University, Email

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