Complex turbulence interaction using massively parallel direct numerical simulations

Chang-Hsin Chen, Agustine Maqui, and Diego Donzis
Department of Aerospace Engineering, Texas A&M University, College Station, TX

Motivation & computational challenge

Most flows of practical interest are turbulent
- High Reynolds numbers \((Re)\) with wide range of spatial and temporal scales

\[
Re = \frac{\alpha L}{\nu} > R_{\lambda}
\]
- \(\alpha\): characteristic velocity
- \(L\): characteristic length
- \(\nu\): kinematic viscosity
- \(R_{\lambda}\): Taylor’s Reynolds number

Controlling turbulence: improved energy efficiency

How do we study turbulence?

Resolving all scales: extreme computational cost
- Domain > \(L\): Integral length scale (largest scale)
- Grid Spacing < \(\eta\): Kolmogorov microscale (smallest scale)

Computational work scales as:

\[
W \propto R_{\lambda}^6
\]

Turbulence control: generation and mitigation

How can turbulence be generated or controlled?
- Classical approach: grid turbulence
- New method: laser-controlled turbulence

Lasers can photo-dissociate molecules
- Fragments with very large velocities + TNE

Two sources of energy (kinetic and internal):

\[
\Delta K_1 = \frac{1}{2} \sum \left( u_i^2 - U_i^2 \right), \quad \Delta \epsilon_1 = \frac{1}{2} \sum \left( u_i^2 \right)
\]

Relative importance parameter:

\[
Q = \frac{\Delta K_1}{\Delta \epsilon_1}
\]

Qualitatively different evolution: \(Q\) controls turbulence

Shock turbulence interaction

When turbulent flows pass through a shock:
- Turbulence characteristics change
- Shock structure weakened
- Thermodynamic quantities \(\neq f(M_t)\)
- Rankine-Hugoint relations no longer applicable

Shock structure quantification:

\[
\Theta \equiv \frac{\left( \Theta - \langle \Theta \rangle \right)^2}{\langle \Theta \rangle} \approx f \left( \frac{M_t}{\Delta M} \right)
\]
- \(\langle \Theta \rangle\): local min (div \(\vec{V}\))
- \(M_t\): turbulent Mach number
- \(\Delta M\): Mach number minus unity

\[
\Theta \propto M_t / \Delta M
\]

Impact

- Controlling turbulence can drastically improve efficiency, reduce drag and friction losses
  - Energy generating technologies, wind farms and hydroelectric turbines
  - Commercial aircraft, hypersonic vehicles
- Novel techniques for shock structure analysis due to shock turbulence interaction
- Understanding interactions can significantly lead to better flow control
  - Accurate calculation of turbulent shock jumps
  - Turbulent characteristics predictable

Shock structure quantification:

\[
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