

*Direct numerical simulation of canonical shock-turbulence
interaction*

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Outline

- Model problem
- Motivation
- Governing equations
- Isotropic turbulence
- Shock-turbulence interaction
- Summary and Future work

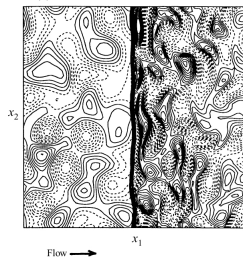
Model Problem

Problem

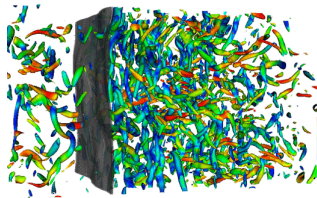
- 3D Isotropic turbulence
- Planar normal shock wave
- 1D uniform mean flow
- No shear, separation, streamline curvature or wall/surface effects

Features

- Amplification of turbulence quantities
- Shock-distortion and unsteadiness



Lee *et al.* JFM 1997

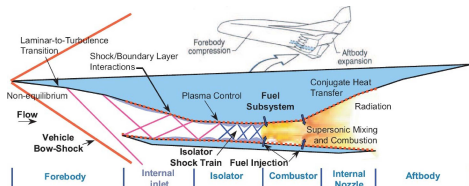


Larsson *et al.*, 2013

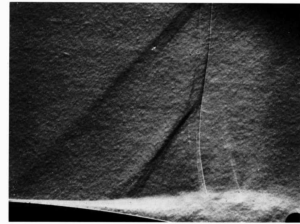
Motivation



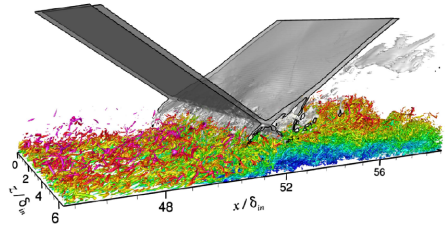
dfr.nasa.gov



Stanford FPCE group

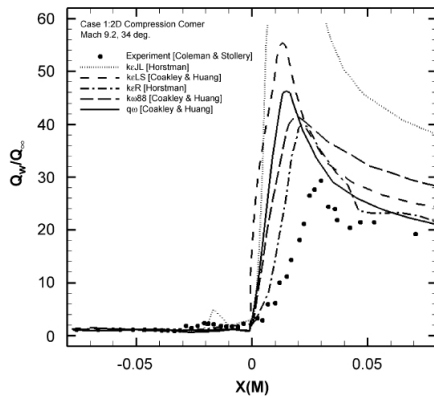


Album of fluid motion, 1982

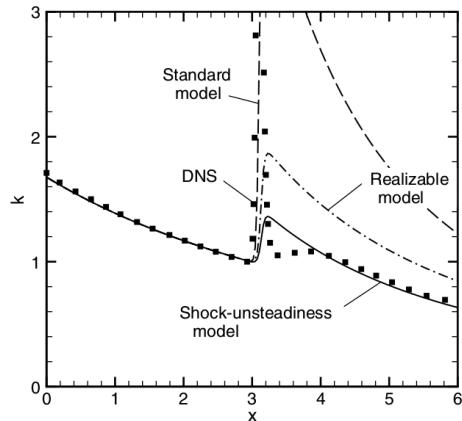


Pirozzoli and Bernardini

Motivation

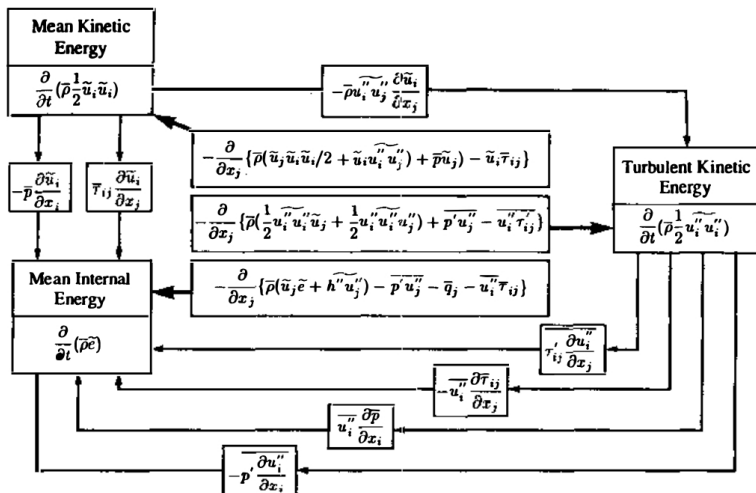


Roy and Blottner, *Prog. Aero. Sci.*, 2006



Sinha and Balasridhar, *AIAA J.*, 2013

Motivation



Lele, ARFM, 1994

Earlier works

Theoretical

- Ribner (1953, 1954, 1985)
- Moore (1953)
- McKenzie and Westphal (1968)
- Mahesh *et al.* (1996)
- Donzis (2012)

Experimental

- Hesselink and Sturtevant (1988)
- Keller and Merzkirch (1990)
- Honkan and Andreopoulos (1992)
- Barre *et al.* (1996)
- Agui *et al.* (2005)

Numerical

- Lee *et al.* (1993, 1997)
- Hannappel and Friedrich (1995)
- Jamme *et al.* (2002)
- Larsson *et al.* (2009, 2013)
- Livescu and Ryu (2014, 2015)

About the code

Governing equations

- Solve 3D unsteady compressible Navier-Stokes equations in Cartesian coordinates

$$\begin{aligned}\partial_t \rho + \partial_k(\rho u_k) &= 0, \\ \partial_t(\rho u_i) + \partial_k(\rho u_i u_k) + \partial_i p &= \partial_k \sigma_{ik}, \\ \partial_t(\rho E_0) + \partial_k(\rho E_0 u_k) + \partial_k(p u_k) &= \partial_k(u_i \sigma_{ik}) - \partial_k q_k\end{aligned}$$

with equation of state,

$$p = \rho R T$$

and auxilliary relations,

$$\begin{aligned}\rho E_0 &= \frac{p}{\gamma - 1} + \frac{1}{2} \rho u_k u_k, \\ \sigma_{ik} &= 2\mu S_{ik}^d, \\ S_{ik} &= \frac{1}{2}(\partial_k u_i + \partial_i u_k), \quad S_{ik}^d = S_{ik} - \frac{S_{mm}}{3} \delta_{ik}, \\ \mu &= \mu_{ref} \left(\frac{T}{T_{ref}} \right)^{3/4}, \quad q = -\frac{\mu c_p}{Pr} \partial_k T\end{aligned}$$

Solver

- Prof. Larsson's code titled "hybrid"
- Written in C++ and parallelized using MPI with non-blocking communication
- Fifth order accurate WENO for shock region
- Sixth order accurate central differencing for the rest



Solving the compressible Navier-Stokes equations on up to 1.97 million cores and 4.1 trillion grid points

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Isotropic turbulence

Isotropic turbulence

- Generate initial condition using a pre-defined energy spectrum

$$E(k) \sim \frac{(k/k_0)^4}{\left[(k/k_0)^4 + C\right]^{17/6}}$$

- Normalize to get isotropic field
- Add thermodynamic fluctuations using pseudo-sound relations
- Temporally evolve to obtain fully developed isotropic turbulence

Consistent initial conditions for the DNS of compressible turbulence

J. R. Ristorcelli

Institute for Computer Applications in Science and Engineering, NASA Langley Research Center, Hampton, Virginia 23681-0001

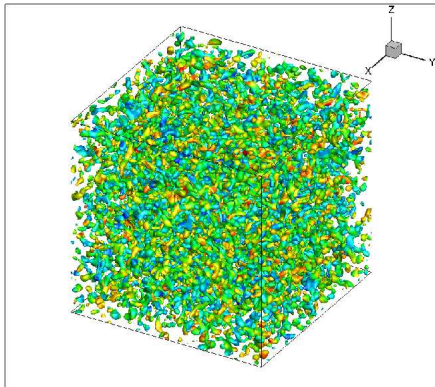
G. A. Blaisdell

School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907-1282

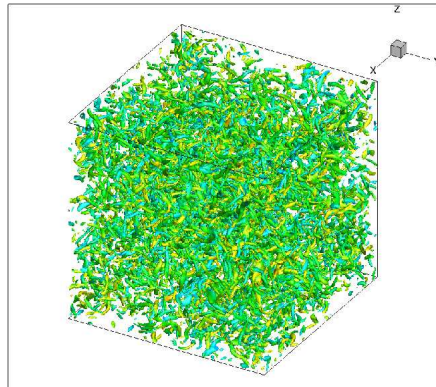
(Received 13 August 1996; accepted 2 October 1996)

Ristorcelli and Blaisdell, Phys. Fluids, 1997

Isotropic turbulence

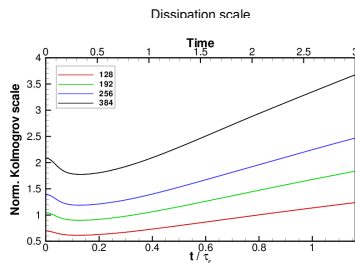
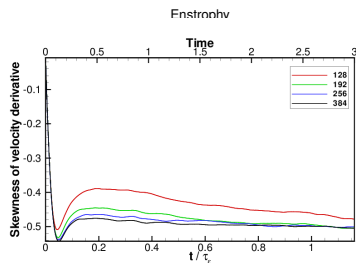
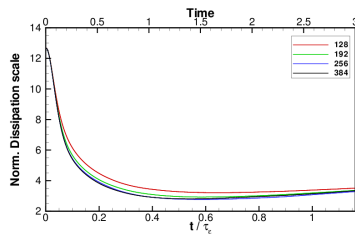
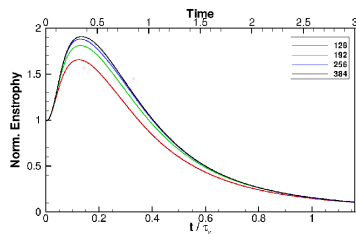


Time, $t = 0$



Time, $t = 2$

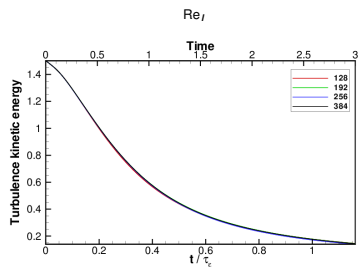
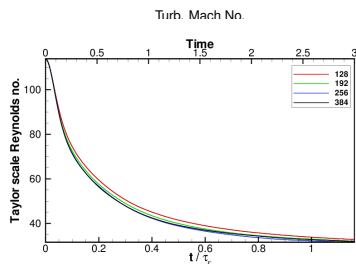
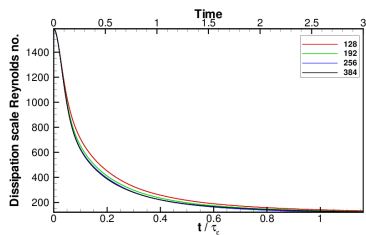
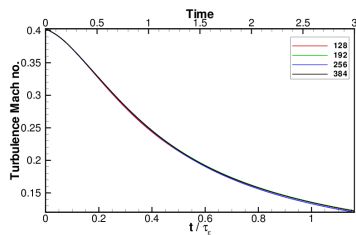
Resolved turbulence



Skewness

Kolmogorov scale

Parameters

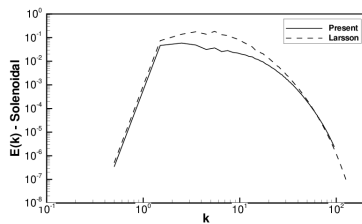


Turb. Mach No.

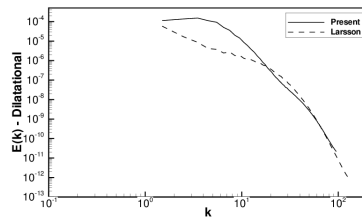
 Re_l Re_λ

TKE

Comparison



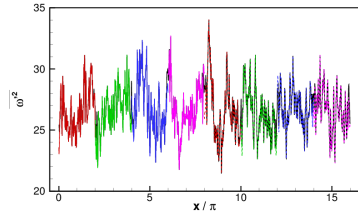
Solenoidal energy



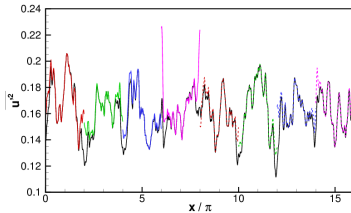
Dilatational energy

Blending of multiple databases

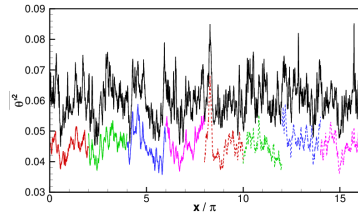
- Requirement of long record in time (by-pass transition)
- Concatenate multiple statistically identical databases
- Less memory and simple
- Removes spurious dilatation but not completely



transverse vorticity



shock-normal velocity



dilatation

Shock-turbulence interaction

STI - Details

- Geometry:

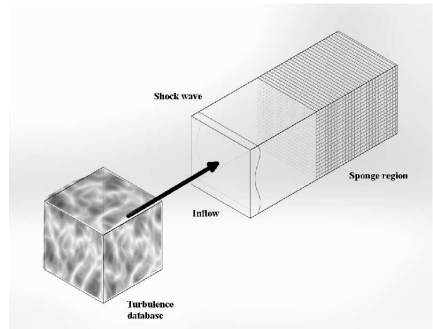
$$N_x \times N_y \times N_z = 1042 \times 384^2$$

- Parameters:

$$M = 1.5, M_t = 0.15, Re_\lambda = 35$$

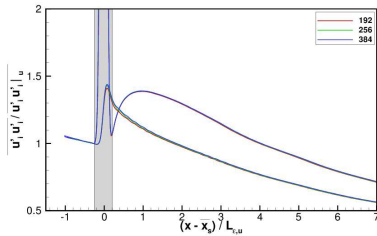
- Run-time:

2 acoustic time-period +
1 inflow turbulence time-period

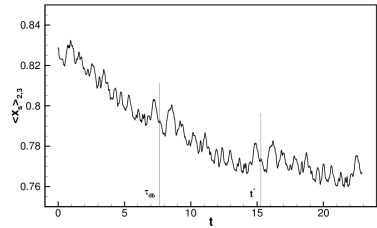


Computational domain

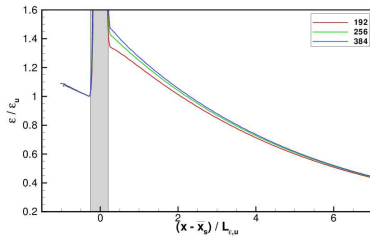
Verification



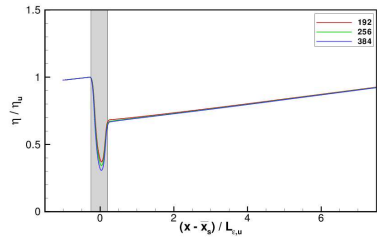
Reynolds stress



Shock drift

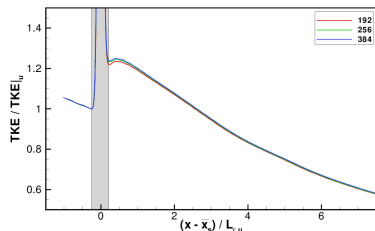


Dissipation of TKE

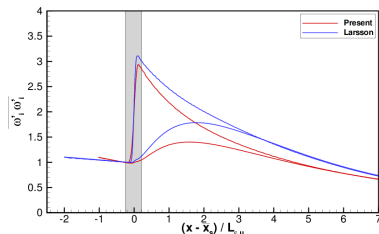


Kolmogorov scale

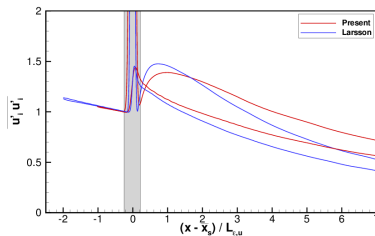
Comparison with existing data



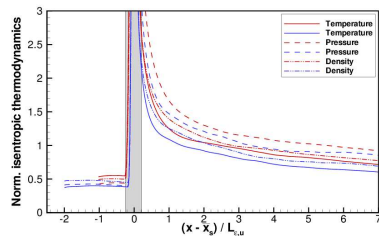
TKF



Vorticity



Reynolds stress



Isentropic relations

Summary and future work

Summary

- DNS of isotropic turbulence
- Shock-captured simulation of isotropic turbulence interaction with normal shock
- Verification of results is important

Take-away message

- TKE increases, length scale decreases, and thus mixing rate increases

Future work

- Gain physical insight of various terms
- RANS is only industrially feasible; Use the understanding to propose better models

Thank you