Hypersonic Technology

High-Speed Strike Weapon
- Scramjet
  - Mach 5-8
- Penetrating Regional
  - ISR / Strike
  - Scramjet
  - Mach ≈5

Tactical Boost-Glide / Prompt Global Strike
- Rocket
  - Mach = 10-20

Space Access
- Rocket
  - Mach 20+
High-Speed Flow Research Team
Computational Sciences Center

• Government Employees
  – Dr. Nicholas Bisek
  – Dr. Ryan Gosse
  – Mr. Eswar Josyula
  – Dr. Joel Malo-Molina
  – Dr. Jonathan Poggie

• Basic Research Contractors
  – Dr. Jon Burt
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• Application Support Contactors
  – Mr. D. Galbraith
  – Mr. W. Humphrey

• AFRL Partners
  – Dr. Mark Hagenmaier (scramjet flows)
  – Dr. Roger Kimmel (transition, SWBLI unsteadiness, flight tests)

• CCAS Partners
  – Dr. Datta Gaitonde (FDL3DI code, SWBLI unsteadiness, BL trips)
  – Dr. Graham Candler (US3D code, thermophysics)
Main Research Themes

1. LES and DES as engineering tools
2. Fatigue loading
3. Inlet flows
4. Selected topics in aerothermal prediction
1. LES and DES as Engineering Tools

- Large-scale computations
- Computational methodology
- Verification and validation

Gosse, US3D, HIFiRE-6

Sherer, HIFiRE-6
Title: Unsteady Pressure and Heating Environment on High-Speed Vehicles with Responding Structures
PI: Dr. Ryan Gosse, AFRL/RQHV

<table>
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- Multi-disciplinary simulations
- Disparate space and time scales
- Utilize significant fraction of machine (10k – 100k cores)
- Develop procedures for large jobs, large data

Garnet / ERDC: 150k cores
Hybrid Parallelism

- Exploit fine-grained parallelism with vectorization and threads (OpenMP)
- Support domain decomposition with MPI
- Minimum block size set by compact difference numerics
- Use threads to scale to more cores at same accuracy
Turbulent Boundary Layer Flow

Density contours, $\rho/\rho_\infty$

M = 2.3, 2.9
Re$_{\theta_i}$ = 2000, 2500
$10^6$ to $10^9$ cells
Up to 32k cores
Up to 8 threads

Poggie et al., AIAA Paper 2014-0423
Poggie, AIAA 2014-xxxx
Comparison to Experiment: Boundary Layer Profiles

Mean Profiles

Streamwise Fluctuations

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Comparison to Experiment: Spatial Correlations

Thus, the pseudo-intermittency can be expressed as:

\[
c = \frac{I_1}{C_0 I_y(\tau)} - \frac{I_1}{C_0} \frac{I_2}{C_0^2} \frac{C_2}{C_1^3}
\]

Figure 7 shows the pseudo-intermittency profile calculated in this manner. An intermittency profile (Selig et al. 1989) derived using a VITA-based threshold technique from hotwire data obtained in the same boundary layer flow is included for comparison. The shape of the profiles is quite similar, but they are offset by about 0.3 \(d\). The offset may well be due to differences in the threshold for defining turbulent fluid.

4.1.2 Correlations

A spatial correlation function was calculated over a set of images between the scattering intensity recorded at each pixel in the field of view and the scattering intensity at a reference location. The correlation coefficient was defined by the following formula:

\[
R_x(r) = \frac{\sum_{i=1}^{N} I_i x(r) / C_0 / C_2^3}{\sum_{i=1}^{N} I_i x(r) / C_0 / C_2^3 + \sum_{i=1}^{N} I_i x(r) / C_0 / C_2^3}
\]

where \(I_i\) is the intensity of scattered light recorded by the video camera, \(x\) is a reference location, and \(r\) is a relative displacement vector. This type of correlation mimics the cross-correlation between a pair of point probes at zero time delay.

Figure 8 shows contour plots of the two-point cross-correlation for several heights in the boundary layer. The domain corresponds to the central third of the field of view in Fig. 4. A set of \(N=400\) images was used to calculate the correlation in each case. The correlation contours are seen to be approximately elliptical in shape. Large regions of high correlation are seen near the middle of the boundary layer (Fig. 8b, c). In contrast, lower correlation levels and shorter length scales occur close to the freestream (Fig. 8a), where only the tips of the bulges reach, and near the wall (Fig. 8d), where fingers of freestream fluid rarely reach.

Another feature of the plots is the changing inclination of the principal axis of the ellipse-like correlation contours. This angle \(\alpha\) was measured graphically from the correlation plots like the examples in Fig. 8, and is plotted in Fig. 9 as a function of height in the boundary layer. The orientation of the principal axis varies from horizontal at the mean boundary layer edge to about 45\(^\circ\) at 0.6 \(d\), where it stays constant until scatter is introduced due to lack of resolution in the flow visualization near the wall.

Quite similar structure angles were observed (Spina et al. 1991b) in space–time correlations of hotwire mass flux data for small wire separations. For a wire separation of 0.09 \(d\), a structure angle of 45\(^\circ\)–50\(^\circ\) was obtained in the range 0.2 \(y/d\) \(\leq 0.8\) (Fig. 10).

A similar correlation analysis has been done of the plan-view images (Poggie 1991), but is omitted here for the sake of brevity. The results showed elliptical correlation contours, elongated in the streamwise direction, with principal axes on the order of 1.0 \(d\) and 0.5 \(d\) at \(y/d = 0.5\). These results are also consistent with hotwire space–time correlations (Spina et al. 1991b).
Boundary Layer Fluctuations: Effect of Domain Width

Density

Mass Flux \((\rho u)'\) 

z-Wavenumber Spectrum

Resolution:
\(\Delta x^+ = 6\)
\(\Delta y^+ = 0.5-9\)
\(\Delta z^+ = 5\)
\(\Delta t^+ = 0.05\)

Increasing \(L_z\)

Downstream View
y-z-plane, \(x/\delta_0 = 100\)
2. Fatigue Loading

- Fatigue loading from unsteady SWBLI very serious design concern
- Typical for Mach 5 Cruise: 147 dB, 800 K (Zuchowski, AFRL TR, 2012)
Separation Bubble as Amplifier

- Plotkin (AIAA J, 1975)
- Linearly-damped Brownian motion
- Time scales: $\tau_u << \tau_R$
- Predicts spectrum, autocorrelation, fluctuation intensity
- Frequency-selective amplifier
- Cut-off frequency set by separation bubble characteristics
- Input set by TBL

Wall Pressure Statistics

Spectrum

\[ G_p(f) = \frac{f G_p(f)}{\sigma_p^2} \]

Autocorrelation

\[ r_b(t) = \frac{b(t)}{\sigma_p^2} \]

\[ G_p(f) \propto 10^{-2} \]

\[ 10^{-1} \]

\[ 10^0 \]

\[ 10^1 \]

\[ 10^2 \]

\[ 10^{-4} \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 10^0 \]

\[ 10^1 \]

\[ 10^2 \]
Flight Test Experiments

HIFiRE-1

Kulite Transducer Stations

- HIFiRE Flight 1: Woomera Range, March 22, 2010
- Documentation: Stanfield, Kimmel, and Adamczak, AIAA Papers (2012-2013)
Wall Pressure Spectra

Experimental Results

Various configurations, $M = 2-5$

Compositional Results

Compression ramp, $M = 2.3, 24$ deg

LES captures large-scale unsteadiness

Effect of Control

- Size of separation bubble
- Energy in low-frequency wall pressure fluctuations
- Fatigue loading

Baseline Case

Control Case

Bisek, Rizzetta, and Poggie, AIAA Journal, 2013

24° Ramp
Mach 2.3
Re₀ = 2000

Reduced:

- Size of separation bubble
- Energy in low-frequency wall pressure fluctuations
- Fatigue loading

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Fluid / Hot Structure Interaction

Large-Scale Separation Shock Oscillation Drives Structural Dynamics

- Non-equilibrium LES with moving grid
- Non-linear structural response

Data: Maestrello and Linden (1970)

R. Gosse
US3D

Supersonic Flow over Deflected Panel

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3. Inlet Flows

- Corner flow interactions
- RANS modeling
- LES
Corner Interactions in Inlet Flows

Mean Flow Streamlines

Inviscid flow incident shock impingement line

Benek, Suchyta, and Babinsky (2014)
RANS Simulations (Overflow, non-eq. k-ω)
M = 2.9, α = 13°, W/H = 1, δ/W = 0.07

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited. 88ABW-2014-3059
Effect of Boundary Layer Blockage on Separation Scale

Scaled

$\Delta x / f \delta$

$\delta / gW$

$M=2.9 \ W=13$
$M=2.9 \ W=10$
$M=2.9 \ W=8$
$M=2.5 \ W=13$
$M=2.5 \ W=10$
$M=2.5 \ W=8$

$\Delta x$

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LES for Corner Flows

Mach 2.3 Turbulent Corner Flow

\[ M = 2.3, \quad Re_\theta = 2400 \]

HFILES, FDL3DI Code

1.06x10^9 cells

13240 processors

\sim 2 \text{ weeks}

N. Bisek, AIAA Paper 2014-0558
Corner-Ramp Configuration

\[ M = 2.3, \quad \text{Re}_\theta = 2400 \]

HFILES, FDL3DI Code
750 Mcells
47040 processors
(5880 tasks x 8 threads)

N. Bisek, AIAA Paper 2014-xxxx
4. Selected Topics in Aerothermal Prediction

RANS for 3D Interactions
23° Sharp Fin
M = 5.0, Re_θ = 7400
DLR Experiments:
Schülein et al. (2001)

Streamwise Profile of Wall Heat Flux

US3D Code
Leger and Poggie, AIAA 2014-0951
Direct Numerical Simulation of Laminar-Turbulent Transition

HIFiRE-1 Boundary Layer Trip Experiment

Flight Test Article

“Pizza-Box” Trip

Wall Heat Flux

Trip

Trip

Cost/run: 3200 processors for 120 hours

Gronvall, Bisek, and Poggie, AIAA Paper 2014-0433
Kimmel and Adamczak, AIAA Paper 2011-3413
State-to-State Kinetics: Influence on Wall Heat Flux

- Master equation for V-V/V-T
  - 48 quantum levels for nitrogen
  - FHO rates
  - Self-diffusion in vibrational states
- Transport coeffs from Wang-Chang Uhlenbeck eqn (Boltzmann equation with internal energy)
- Contributions to heat transfer: heat conductivity (HC), thermal diffusion (TD), mass diffusion (MD), and diffusion of vibrational energy (DVE)

\[ \frac{\partial \rho_{ci}}{\partial t} + \nabla \cdot \left[ \rho_{ci} \left( v + V_c + \tilde{V}_{ci} \right) \right] = \dot{\omega}_{ci} \]

\[ q = q^{HC} + q^{TD} + q^{MD} + q^{DVE} \]

Contribution of Heat Conduction to Total Heat Flux

Josyula et al, 2014
Unsteady Scramjet Flameholder

- Mach 2 cavity flameholder simulated using hybrid RANS/LES (US3D)
- Compared to PIV data
- Characterization of turbulence and mixing in cavity for non-reacting cases

Streamwise velocity profiles for RANS (red) hybrid RANS and LES (black) and experiment (symbols)

Instantaneous fuel mole fraction for 56SLPM and 99SLPM cases

Mean fuel mole fraction for 56SLPM and 99SLPM cases


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Summary

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2. Fatigue loading
3. Inlet flows
4. Selected topics in aerothermal prediction