Large Eddy Simulations of Aero-Optic Distortions

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What is Aero-Optics?

• **In short**: The distortion of an optical beam caused by turbulent compressible flow

Distortions are caused by non-uniform index-of-refraction field resulting from turbulent density fluctuations and small amplitude distortions in the near field can cause severe performance degradation in beam intensity and fidelity.

• Major impediment to applications of airborne optical systems for communication, imaging, targeting, and directed energy systems.
Current Work

- Want to use Computational Fluid Dynamics (CFD) to improve our understanding and our predictive capability of aero-optics systems at realistic Reynolds and Mach numbers.

\[ Re = \frac{\rho V D}{\mu} \quad Ma = \frac{V}{c} \]

Simulations of the optical turret used on Notre Dame’s Airborne Aero-Optical Laboratory (AAOL) using wall-modeled Large-Eddy Simulation (LES).

LES of weakly compressible mixing layers to investigate aero-optics fundamentals.
Flow Solver

- Large-eddy simulation (LES) solves the spatially filtered Navier-Stokes, continuity, and energy equations and provides modeling to account for the scales smaller than those resolved by the computational grid.
- Unstructured mesh, compressible LES code CharLES developed at Cascade Technologies Inc. (Khalighi et al. 2011).
- Low-dissipative finite volume for spatial discretization:
  - Non-dissipative central flux blended with a dissipative upwind flux to provide computational stability when the mesh quality is not ideal.
  - The amount of upwind dissipation is minimized and determined by local mesh skewness.
  - Formally 2nd order but recovers 4th order Euler fluxes in uniform Cartesian mesh.
- Wall-model utilized for wall-bounded flows, solves simplified Thin Boundary Layer equations on an embedded mesh to get approximate BC’s for the wall.
- Third-order Runge-Kutta in time.
- Parallelized using MPI.
Wall Model Method

- Resolving the turbulence near a wall in high Reynolds number flows is cost prohibitive in high-fidelity CFD (Choi and Moin, 2012)

- By solving the simplified Thin Boundary Layer equations on an embedded mesh, the wall shear stress $\tau_{wm}$ and heat flux $q_w$ are imposed as approximate boundary conditions to the near-wall cell for LES calculations.

- In only resolving the outer scales of the boundary layer, LES at the Reynolds numbers of some engineering systems becomes possible where it was previously cost prohibitive.
Hemisphere-on-Cylinder Turret Simulations

Simulation Details

Coarse Mesh: 83M CV’s
Fine Mesh: 200M CV’s
Domain: 15D × 5D × 10D
Re_D = 2,300,000
M_∞ = U_∞ / c_∞ = 0.4

Interested in:
• How does the optical distortion change with respect to viewing angle, aperture size?
• What physical mechanics in the flow are related to optical distortion magnitude/behavior?
• Can we use information from the flow field to predict/understand optical behavior?

Over the past year:
• Doubled the runtime of finest simulation
• Ran coarse mesh simulation to examine mesh dependence
• Processing the >100 TB of data on Blue Waters nearline system
Mesh and Experimental Result Comparisons

Coefficient of pressure along the turret centerline for fine and coarse resolution results compared with wind tunnel measurements.

- Fine Mesh
- Coarse Mesh
- Experimental Measurement (Gordeyev et al., 2007, 2010)
Optics Solver

- To compute the optics, beam grids are embedded in the computational mesh and computed using geometric optics.

- At each time step when the optics are calculated, the density is interpolated from the LES mesh using a second-order method, and the index of refraction is calculated and integrated along the beam propagation path.

- Parallelized by integrating segments on each processor and compiling at the end using a collective communication.

\[
\text{OPL}(x, y, t) = \int_{s_0}^{s_1} n(x, y, z, t) \, ds
\]
Optical Results – Centerline in Wake

Aberrated Wavefront

Nearfield Intensity Pattern

Initial Beam Distribution

Increasing Lookback Angle

110°

130°

150°

Z = 16000D
Optical Distortion Measurements

Comparison with wind tunnel measurements of $\text{OPD}_{\text{RMS}}$, a measure of optical distortion, along the centerline of the turret.

Average optical distortion measurements between coarse and fine mesh are close but don’t show the level of grid insensitivity seen in other flow quantities.
Aero-Optics – Viewing Angle Domain

- Optical data integrated and collected at 390 different angles
  - Each time optics are calculated 5.4 million points per angle, 2.1 billion points in all are interpolated and integrated over
  - In all, ~3 TB of optical data was generated

Optical beam centers denoted by black dots

*OPD*$_{rms}$ Field Map
The optical distortion magnitude of a large number of viewing angles can be related by a single parameter, the lookback angle. What about the points that don’t collapse?
Contour of normalized $\text{OPD}_{\text{rms}}^{\text{norm}}$. Markers denote centers of optical beams at data points – red markers fall within linear region, blue do not.

Support vector machine classification of data that does and does not fall within linear region, shows viewing angles affected by horn vortices.

Find that beam angles that do not collapse onto the linear region are near the horn vortices.
Aero-Optics – Effect of Aperture Size on Optical Behavior

Boundary of the horn vortex region for apertures of different sizes.

Line fit along the collapsed portion of the $OPD_{RMS}$ vs. lookback angle figure for different aperture sizes.
Developed a parallel solver for Proper Orthogonal Decomposition (POD, PCA) and Dynamic Mode Decomposition (DMD) to more fully explore the dynamics of the turret flow and aero-optics. Computation requires the calculation of the economy SVD of a dense matrix, large memory and I/O requirements to compute efficiently.

Computational method modified from the the TSQR method described by Demmel et al. (SIAM J. Sci. Comp.), Sayadi et al. (CTR Briefs, 2013) on 1024 XE Nodes using 200.5M data points and 2000 snapshots (~3TB). Implemented with MPI, LAPACK, and BLAS.
Optical Behavior of Shear Layers

To study the spectral behavior of aero-optic phase distortions and the link to density fluctuations, high-fidelity large-eddy simulations of two weakly-compressible shear layers were computed.

Contours of density, \( \rho \), for density matched and mismatched shear layer simulations.

\[
\frac{\rho_{\text{bottom}}}{\rho_{\text{top}}} = 1.0
\]

\[
\frac{\rho_{\text{bottom}}}{\rho_{\text{top}}} = 1.3
\]

\( P \) dominated small-scale optical distortions

\( T \) dominated small-scale optical distortions

These are then compared with theoretical results derived using statistical fluid mechanics and wave propagation theory.
Weakly-Compressible Shear Layer Simulations

Mixing layer simulation set-up is similar to that of Pantano & Sarkar (JFM, 2002)

- Reynolds number is 10x larger to capture more of the inertial range of turbulent spectrum
- Resolution is 2x greater
- LES SGS is used to model subgrid scale effects

Data is averaged over 3 ensemble simulations for each case and over small time periods.

\[ M_C = \frac{\Delta u}{c} = 0.3 \]

Mesh dimensions

1200 \( \times \) 696 \( \times \) 300 CV's
345\( \delta_{\theta,0} \) \( \times \) 200\( \delta_{\theta,0} \) \( \times \) 86\( \delta_{\theta,0} \)

Reynolds Number \((\text{Re}_\theta = \frac{\Delta u \delta_\theta}{\nu})\)

\[
\begin{align*}
\text{Re}_{\theta,0} &= 1600 \\
\text{Re}_{\theta,f,s=1} &= 14292 \\
\text{Re}_{\theta,f,s=1.3} &= 13707
\end{align*}
\]
Comparisons of Turbulence Quantities with Previous Work

Comparison of turbulence information of density matched shear layer against data from two DNS simulations and two experimental measurements.
Theoretical and computational results show that the 1D spectral behavior of optical phase distortion follows a spectral slope of $\gamma_\phi = \gamma_\rho + 1$.

\[ E_\rho(\kappa) \propto \kappa^{-\gamma_\rho} \]

\[ E_{OPD}(\kappa) \propto \kappa^{-(\gamma_\rho + 1)} \]

The value of $\gamma_\phi$ is strongly dependent on the influence of temperature or pressure effects in density fluctuations.
P/T Behavior of Aero-Optical Distortions

Approximating OPD into contributions due to pressure (OPD_p) and temperature (OPD_T).

\[
OPD = \int_{s0}^{s1} K_{GD} \rho' dz \quad \Rightarrow \quad OPD \approx K_{GD} \int_{s0}^{s1} \bar{\rho} \frac{P'}{\bar{P}} dz - K_{GD} \int_{s0}^{s1} \bar{\rho} \frac{T'}{\bar{T}} dz
\]

Autocorrelation of temperature and pressure OPD components for two simulation cases.

Structure and intensity of optical distortion caused by pressure is largely unaffected, Structure and intensity of optical distortion caused by temperature is greatly affected.
Wrap Up / Acknowledgements

Using Blue Waters to study fundamental and applied aero-optic systems:

• Able to efficiently process and explore >100 TB of flow and optical data created by high-fidelity simulations to study effects of turbulent wake structure, viewing angle, and aperture size on hemisphere-on-cylinder turret optics
  • Solver for data driven decompositions developed and used to crunch several TB’s of data at a time

• Link between the behavior of optical phase distortion and other flow quantities can be studied using ensemble simulations with different system parameters

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Extra Slides
This method reduces the memory requirement of the SVD when using a large number of cores (from $\sim 2pn^2$ to $\sim n^2 \log_2 p$)
Wavefront Reconstruction with POD Modes

Large-scale flow structures in the turret wake have a larger optical impact on off-centerline viewing angles than their centerline counterparts.

At off-centerline angles, large-scale structures have more effect on higher-order Zernike modes that are difficult to correct with adaptive optics methods.

Can be corrected via piston and fast-steering mirrors.
Global Density POD Modes – Time Coefficient Spectra

Mode 1

Mode 2

Mode 3

Mode 4

Mode 5

Mode 6
Global Density POD Modes – Time Coefficient Spectra

Linear Region Angle

Horn Vortex Angle
• With Blue Waters, able to solve for nearly 400 viewing angles encompassing the entire turret viewing area.

• Each beam contained 5.4 million points – each time optics are calculated, ~1.5 billion points are interpolated and integrated. Generated >2 TB of optical data in all.
Challenges for Computational Aero-Optics

• Prediction of aero-optical distortions requires the capturing of optically relevant flow scales

• Mani et al. (2008) showed that this requirement can be fulfilled by adequately resolved Large-Eddy Simulation (LES)
  • LES solves the spatially filtered Navier-Stokes, continuity, and energy equations and provides modeling to account for the scales smaller than those resolved by the computational grid

• Resolving the turbulence near a wall in high Reynolds number flows is cost prohibitive in high-fidelity CFD (Choi and Moin, 2012)
  • \( N_{total} \propto \text{Re}_L^{37/14} \) for DNS
  • \( N_{total} \propto \text{Re}_L^{13/7} \) for wall resolved LES
  • \( N_{total} \propto \text{Re}_L \) to resolve outer scales of boundary layer in LES
Wall Model Method

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- In only resolving the outer scales of the boundary layer, LES at the Reynolds numbers of some engineering systems becomes possible where it was previously cost prohibitive.
CharLES Scaling on Blue Waters

Mean time to solve 25 steps - 192M CV Mesh

- Actual
- Ideal

Cores
What is the actual roll-off of T and P?

**Temperature**

K41 dimensional scaling predicts a 5/3 roll off for temperature.

However in shear flows, the spectral slope of temperature starts at 4/3 for low Taylor-scale Reynolds numbers and tends towards 5/3 for very high turbulent Reynolds numbers.

In grid turbulence, spectral slope quickly approaches 5/3 with increasing Reynolds number.

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**Figure 4** The variation in the spectral slope for various passive scalar spectra as a function of $R_\lambda$. For shear flows (filled squares), there is a slow evolution toward 5/3, which appears to be approached at large $R_\lambda$ (>2000). The filled circles are the spectral slopes for grid turbulence experiments (no shear). They are close to 5/3 even at very low $R_\lambda$. The shear-flow graph is from Sreenivasan 1996 (see also Sreenivasan 1991). The grid turbulence results are from Mydlarski & Warhaft 1998a.

Warhaft, 2001 Annual Review Fluid Mech
What is the actual roll-off of $T$ and $P$?

Pressure is harder to define, presence of K41 predicted 7/3 roll-off does not appear clear until larger Taylor-scale Reynolds numbers (>600).

- **5/3**
  - Tsuji & Ishihara 2003. Exp Turb Jet
  - Inertial Range is smaller & at higher

- **6/3 -> 7/3**
  - Gohto Fukayama 2001. DNS Turb in box up to $Re_\lambda = 478$.

- Small range at 7/3, appears to be lower

Vedula & Yeung 1999. DNS Turb in box up to $Re_\lambda = 235$. 