An Assessment of CFD-based Aero-Optics Modeling using Flight Test Data from the Airborne Aero-Optics Laboratory

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**MZA Associates Corporation

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• Colleagues/Collaborators/Coauthors at MZA Associates Corporation
  • Dr. Mathew Whiteley, Dr. David Goorskey, Richard Drye
• Colleagues/Collaborators at Kratos/Digital Fusion
  • Jennie Barber, Ricky Brown
• Brief Description of the AAOL Program and of the CFD Modeling Goals
• CFD-AO Model
• CFD Model of the AAOL for this study
• Summary of CFD Study To Date
  • Mesh and Time Refinement Study
• Detailed Investigation of Modeling Effects upon Modeled Distortions
• Conclusions and Discussions
Airborne Aero-Optics Laboratory (AAOL)
HEL-JTO Funded, AFOSR Grant

- Small-Aperture Diverging Beam/Beacon
- Negligible Aero-Optic Effects
- Overfill AAOL Aperture x 2

- 4” Clear Aperture, 12” Tracking Turret
- Spherical Wavefront “unaffected” by Tip/Tilt at source
Primary Goals: **Aero-Optical and Aero-Mechanical Distortion Modeling**
- Model the near turret aero-optical distortions and compare to measured
- Model the unsteady aero-mechanical forcings on the turret, and pass these to a detailed FEM and waveTrain model

Secondary Goals: **Evaluate Aero-Effects Modeling Capability**
- Investigate the flow fields produced by the CFD and correlate flow features to aero-optical and aero-mechanical distortions
- Investigate effects of numerics (turbulence/LES models, convective discretizations and others) upon modeled aero-optical and aero-mechanical distortions

Approach:
- Use CFD modeled resolved density field (index of refraction) to compute Optical Path Difference, and correlate to the measured aero-optical disturbances
- Correlations of wave front error statistics and flow behavior
  - WFE PSD: Power Spectral Density vs. frequency
  - WFE POD: Proper Orthogonal Decomposition mode shapes and strengths
- Produce unsteady pressure forcing on turret outer mold line
  - Process and pass to FEM model

Foci of this briefing:
- Compare computed and measured aero-optical distortions
- Evaluate discretization and DES model effects upon aero-optical distortions
CFD-AO Model

• Specialization/Customization of the NASA OVERFLOW CFD model specifically for aero-optics applications
  • CFD-AO: Developed under AFRL/RBAT funding: Dr. Scott Sherer/TPOC

OVERFLOW
• Very capable CFD model that has been under continuous development and improvement for 20+ years
• Chimera/Overset Grid System, Finite-Difference, Sophisticated Reynolds-Averaged Navier-Stokes (RANS), Hybrid RANS/LES (Detached Eddy Simulation) Models, Massively-Parallel, Very Efficient, Wide User Base and it’s free!

Highly-Resolved, Massively-Parallel, Unsteady, Detached Eddy Simulation Modeling Capability
CFD-AO Model

• C++ class library and accompanying pre- and post-processors designed for incorporating aero-optical related data processing into generic CFD models, specially integrated into OVERFLOW version 2.2c

OVERFLOW Integration
• Implementation of a handful of CFD-AO “public” library API
• Given a CFD grid system, beam grid is used to pre-process CFD-AO
• Able to compute beam propagation on the fly using a spectral/parabolic Paraxial Beam solver
  • Use specializations to improve processing rates and data footprints
• Wide variety of pre- and post-processing tools

Beam Grids
• Pre-compute and Store CFD-to-Lattice Interpolants
Two specializations made under this project:
- In-Line Optical Path Difference Calculations and Data Storage
- Point-Cloud Pressure Interpolation and Data Storage

**In-Line OPD Calculation**
- Integrate Optical Path Difference integral at specified time steps and wavelength “on the fly” as opposed to post processing
- Output each OPD field into NetCDF file

**Point-Cloud Pressure Interpolation**
- Interpolate Pressure onto any collection of points (“point cloud”)
- Store interpolated pressure in NetCDF file
- Alleviates awkward existing methods in OVERFLOW (“FOMOCO”, “BC201”)

[Images and charts related to OPD r.m.s. and AAOL Turret]
AAOL CFD Model: Geometric Model and Grid System

- CAD data supplied from AFRL
  - Removed wing: Turret should be far enough away as to not be influenced by wing
  - Extended fuselage: No aft fuselage geometry
  - Incorporated Turret model, allowing elevation and azimuth change
Essentially 3 Phases of CFD modeling accomplished to date:
- Mesh and time step refinement study
- Initial evaluation of effect of look-back angle
- Investigation of numerics impact upon modeled aero-optical distortions

Initial phase of work focused upon $(Az, El) = (128^\circ, 69^\circ)$ for three flight conditions:
- $M=0.4$, $h=5$ km.
- $M=0.5$, $h=5$ km.
- $M=0.61$, $h=8$ km.

All computations made at $AOA=3$ degrees, and Azimuth measured relative to aircraft axis

Inspection of flow field, WFE PSD, shear layer structure etc. led us to devise a finer grid system with more resolution made over the turret aperture
- Initial grid system contains $26 \times 10^6$ grid points in 16 grid zones
- Refined grid system contains $36 \times 10^6$ grid points in 18 grid zones with extra resolution applied over turret aperture and surrounding grids

Details regarding specific numerics for the mesh and time step phase of study:
- Spatial: HLLC, 2nd order, limited
- Temporal: 2nd order dual time stepping using LU-SSOR
- SST Delayed, Detached Eddy Simulation
General Flow Features and Behavior

• “Oil Flow” patterns generated by computing surface-constrained streamlines using first grid surface away from walls and time-averaged flow quantities

• Clearly defined wake, necklace vortices confluence, liftoff, upstream influence of turret, horseshoe vortex, wake recirculation

• Migration of flow from “top” to aperture, from “back” to aperture, from “bottom” to aperture, with liftoff, feeding shear layer and general wake unsteadiness
AAOL CFD Model: Coarse and Fine Grid Systems

Original Grid System (Coarse)

Refined Grid System (Fine)

Refined Grid System over aperture
• Evaluation of CFL number using computed flow fields on the fine grid system indicated that the time step needed to be reduced as well, to keep the CFL number approximately 1.
• Careful matching of CFD and beam grid resolution resulted in a refined and shortened beam grid as well.

<table>
<thead>
<tr>
<th>Mach</th>
<th>Baseline</th>
<th>Refined Grid</th>
<th>Refined Grid, Beamgrid and Timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>5.66E-05</td>
<td>5.66E-05</td>
<td>5.66E-06</td>
</tr>
<tr>
<td>0.5</td>
<td>4.53E-05</td>
<td>4.53E-05</td>
<td>4.53E-06</td>
</tr>
<tr>
<td>0.61</td>
<td>3.86E-05</td>
<td>3.86E-05</td>
<td>3.86E-06</td>
</tr>
</tbody>
</table>

Baseline and Baseline Refined Beam Grid

<table>
<thead>
<tr>
<th>Lx=Ly (m)</th>
<th>Lz</th>
<th>Nx</th>
<th>Ny</th>
<th>Nz</th>
<th>dx=dy (m)</th>
<th>dz (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0.1431925</td>
<td>1.5234</td>
<td>101</td>
<td>101</td>
<td>1.432E-03</td>
<td>7.617E-03</td>
</tr>
<tr>
<td>Refined Grid</td>
<td>0.1431925</td>
<td>0.5080</td>
<td>101</td>
<td>101</td>
<td>1.432E-03</td>
<td>2.540E-03</td>
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<tr>
<td>Refined Grid, Beamgrid and Timestep</td>
<td>0.1431925</td>
<td>0.5080</td>
<td>101</td>
<td>401</td>
<td>1.432E-03</td>
<td>1.270E-03</td>
</tr>
</tbody>
</table>

Shortened and Refined Beam Grid
Coherent Structures Near Aperture Window  
M=0.4, h=5km

Density contours on beam grids

- Baseline (coarser) grid is not picking up fine enough features in turret shear layer
- Refined grid does a better job capturing the features, but is driven too hard with too large of a time step, resulting in more dispersive behavior
- Refined grid and time appears to capture coherent roll up in the shear layer better with smoother, less dispersive behavior
Comparison of CFD-produced Aero-Optics to Flight Test Data: PSD and POD of WFE

Overall Conclusions
• Need refined grid over aperture with appropriate time step
• Modes and high order behavior captured well in PSD in “mid-frequency” range

Can results be improved with different convective schemes? Turbulence models?

Increasing POD Mode Number
Evaluation of Convective and DES Models

- Focus upon the M=0.4 case, and evaluate different combinations of convective scheme discretizations, DES models and other effects, such as sub-iterative convergence.

<table>
<thead>
<tr>
<th>&quot;Generation&quot;</th>
<th>Convective Scheme</th>
<th>DES Model</th>
<th>NITNWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3</td>
<td>HLLC, 2nd Order, vanAlbada Limiter</td>
<td>SST-DDES</td>
<td>3</td>
</tr>
<tr>
<td>G4</td>
<td>HLLC, 2nd Order, vanAlbada Limiter</td>
<td>SST-DDES</td>
<td>10</td>
</tr>
<tr>
<td>G5</td>
<td>Central, 2nd Order, Matrix Dissipation</td>
<td>SST-DDES</td>
<td>10</td>
</tr>
<tr>
<td>G6</td>
<td>Central, 2nd Order, Matrix Dissipation, DIS4=0.08</td>
<td>SST-DDES</td>
<td>10</td>
</tr>
<tr>
<td>G7</td>
<td>HLLC, 2nd Order, vanAlbada Limiter</td>
<td>D-MS</td>
<td>5</td>
</tr>
<tr>
<td>G8</td>
<td>Central, 2nd Order, Matrix Dissipation</td>
<td>D-MS</td>
<td>5</td>
</tr>
</tbody>
</table>

- Other related OVERFLOW settings:
  - FSONWT=2.0, ILHS=16 (typically, although much faster processing, yet less robust, using ILHS=4), FSOT=1, ICC=1
  - Typically run 12,000 steps, with recording over last 6,000 (fSt=420 steps)
  - Compare PSD of WFE, R.M.S. of WFE over aperture, POD
  - Side-by-side comparison of contours near aperture for “Generation” combinations that make sense.
Evaluation of Convective and DES Models

- Central (G5, G6 and G8) and Upwind (G3, G4 and G7) form 2 distinct “roll offs”:
  - Slopes the same, but roll off begins earlier with the upwind schemes
- Both over predict WFE
- Central schemes have rounder PSD shape
- Upwind schemes have a double “hump”:
  - Ringing/Interference at overset boundaries or limiter problems?
  - Increased sub-iterations for upwind reduces hump peaks, but still there…
Evaluation of Convective and DES Models

- All schemes over predict rms WFE
- Central (G5, G6 and G8) show some smaller features than the Upwind (G3, G4 and G7)
- G1 is coarse grid, coarse time step upwind
- G2 is fine grid, coarse time step upwind

<table>
<thead>
<tr>
<th>Generation</th>
<th>rmsWFE ([µm/m])</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3</td>
<td>2.73</td>
</tr>
<tr>
<td>G4</td>
<td>2.79</td>
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<tr>
<td>G5</td>
<td>2.8</td>
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<tr>
<td>G6</td>
<td>2.94</td>
</tr>
<tr>
<td>G7</td>
<td>2.76</td>
</tr>
<tr>
<td>G8</td>
<td>2.56</td>
</tr>
<tr>
<td>AAOL</td>
<td>1.87</td>
</tr>
</tbody>
</table>
Evaluation of Convective and DES Models

- Sign of mode not important
- Mode spatial frequency increases to the right
- All the resolved “Generations” (i.e.: G3-G8) replicate the POD modes to the AAOL data well
- Difficult to ascertain differences between the Central and Upwind schemes (G5, G6 and G8) vs. (G3, G4 and G7)
- Can see better resolution of higher modes with increased Newton sub-iterations (G3 to G4)

Next: One-to-one comparisons of flow quantities near aperture for scheme combinations that “make sense”
**G3-to-G4: Sub-iterative Convergence**

- Contours in cutting plane located 4 cm above aperture window
- Upwind, SST-DDES
- Beam box outline shown

- Extra sub-iterations (3 to 10) removes some “noise” shown in Mach contours
- Density variances similar
- rms WFE not effected
- PSD shows reduction in double hump peaks, but overall, very similar
• Contours in cutting planes located 1 and 4 cm above aperture window
• SST-DDES for both
• “Extra” sub-iterations for both
• Upwind, van Albada
• Central, IDISS=4

• Fine-scale flow features resolved with the central scheme
• Features smoothed with the upwind scheme
G4-to-G5: Central vs. Upwind, SST-DDES

- Contours in cutting planes located 1 and 4 cm above aperture window
- SST-DDES for both
- “Extra” sub-iterations for both
- Upwind, van Albada
- Central, IDISS=4

- More resolved density fluctuations near aperture with central scheme
- Both look similar farther away from the aperture
G7-to-G8: Central vs. Upwind, D-MS

- Contours in cutting planes located 1 and 4 cm above aperture window
- D-MS for both
- “Extra” sub-iterations for both
  - Upwind, van Albada
  - Central, IDISS=4

- Fine-scale flow features resolved with the central scheme near aperture get smoothed out/dissipated farther away

HLLC, Limited

Central, Matrix Dissipation
G7-to-G8: Central vs. Upwind, D-MS

- Contours in cutting planes located 1 and 4 cm above aperture window
- D-MS for both
- “Extra” sub-iterations for both
- Upwind, van Albada
- Central, IDISS=4

- Resolved density fluctuations near aperture with central scheme dissipated at further distance
- Upwind scheme does not resolve these near, but does generate them further away
G5-to-G6: Central, Default DIS4 vs. DIS4*2

- Contours in cutting planes located 1 and 4 cm above aperture window
- SST-DDES for both
- “Extra” sub-iterations for both
- Central, IDISS=4 for both
- Default DIS4 (G5, left)
- Default DIS4*2 (G6, right)

- Extra smoothing with increased 4-th order smoothing coefficient
- Causes increase in WFE, PSD
G5-to-G6: Central, Default DIS4 vs. DIS4\(^*2\)

- Contours in cutting planes located 1 and 4 cm above aperture window
- SST-DDES for both
- “Extra” sub-iterations for both
- Central, IDISS=4 for both
- Default DIS4 (G5, left)
- Default DIS4\(^*2\) (G6, right)

- Extra smoothing with increased 4-th order smoothing coefficient
- Causes increase in WFE, PSD
G4-to-G7: SST-DDES vs. D-MS, Upwind

- Contours in cutting planes located 1 and 4 cm above aperture window
- HLLC, van Albada for both
- “Extra” sub-iterations for both
- Delayed, Multi-Scale (left)
- SST-DDES (right)

- D-MS shows more smoothing (dissipation) although the two are similar
G4-to-G7: SST-DDES vs. D-MS, Upwind

- Contours in cutting planes located 1 and 4 cm above aperture window
- HLLC, van Albada for both
- “Extra” sub-iterations for both
- Delayed, Multi-Scale (left)
- SST-DDES (right)

- D-MS shows more smoothing (dissipation) although the two are similar
G5-to-G8: SST-DDES vs. D-MS, Central

- Contours in cutting planes located 1 and 4 cm above aperture window
- Central, matrix dissipation, default DIS4
- “Extra” sub-iterations for both
- Delayed, Multi-Scale (right)
- SST-DDES (left)

- Contrasted with the upwind comparison, the two show big differences in resolved fluctuations and dissipation rates
- D-MS resolves more features near aperture and dissipates them faster
G5-to-G8: SST-DDES vs. D-MS, Central

- Contours in cutting planes located 1 and 4 cm above aperture window
- Central, matrix dissipation, default DIS4
- “Extra” sub-iterations for both
- Delayed, Multi-Scale (right)
- SST-DDES (left)

- Contrasted with the upwind comparison, the two show big differences in resolved fluctuations and dissipation rates
- D-MS resolves more features near aperture and dissipates them faster
Conclusions

• Some new capability has been added to the CFD-AO model for this work:
  • “In-line” OPD calculations: reduced data footprint
  • “Point Cloud” pressure interpolations: Disconnects CFD mesh from pressure data points
• The CFD produced wave front error can match the flight test data well, but is sensitive to:
  • Mesh resolution
  • Temporal resolution
• Study comparing convective and DES models shows that:
  • Central scheme with matrix dissipation resolved flow and density fluctuations better than the limited upwind (HLLC) scheme
  • Increasing the default 4th order dissipation coefficient increases smoothing, but raises WFE
  • When using the central scheme, the D-MS model appears to dissipate the turbulent fluctuations more quickly than the SST-DDES model away from the aperture but resolves the fluctuations better near the aperture
  • But, when using the upwind scheme, the D-MS and SST-DDES models show similar results. This is presumably due to the central scheme resolving the smaller scale fluctuations which get dissipated more quickly.
Proper Orthogonal Decomposition (POD)

Sequence of Wavefronts: (column vectors)

\[ K = \begin{bmatrix} x_1 & x_2 & x_3 & \ldots & x_L \end{bmatrix} \]

Singular Value Decomposition:

\[ K^T = U \Sigma V^T \]

Coefficients: (rows of)

\[ Q = U \Sigma \]

Modes: (columns of)

\[ V \]

Modal Variance:

\[ \sigma_k^2 = \frac{1}{L-1} \sum_{l=1}^{L} (p_k(t_l) - \langle p_k(t_l) \rangle)^2 \]

\[ \sigma_1^2 > \sigma_2^2 > \sigma_3^2 > \cdots \]

\[ \varepsilon_{ap}^2 = \sum_{k=1}^{\text{rank}(K)} \sigma_k^2 \]

Properties of POD Modes:

- Orthonormal
- Statistically independent
- Data-driven mode shapes
- Ordered by modal variance
- Static, mode shapes stay constant, only magnitudes vary over time
- “Best” representation in the least squares sense
- Each mode has whole spectrum of frequency content

Modal Decomposition of Wavefronts:

\[ \phi(x_n, y_m, t_l) = \sum_{k=1}^{K} p_k(t_l) P_k(x_m, y_n) \]