Wind Tunnel Validation of a CFD-Based Aero-Optics Model

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Abstract: A computational fluid dynamics (CFD)-based aero-optics validation study was conducted at 1:1 scale in wind tunnel tests. Validation was based on fluid mechanical and optical measurements. A 12” diameter hemisphere-on-cylinder turret was tested in the US Air Force Academy 3 ft X 3 ft subsonic wind tunnel, at flow speeds ranging from Mach 0.3 to Mach 0.5. Flow validation was based on mean and rms velocity, mean pressure profile, rms unsteady pressure, and separation point. Optical validation was based on rms phase variance and in-flow phase correlation length derived from two-dimensional Hartmann wavefront sensor data, measured over a 5-inch beam diameter. The CFD code used a two-equation turbulence model with Partially-Averaged Navier-Stokes (PANS) approach. Measurement and prediction show generally good agreement over line-of-sight angles ranging from 60 to 132 degrees.

Nomenclature

\[ C_P = \text{static pressure coefficient} \]
\[ E\{\ldots\} = \text{expectation value} \]
\[ F = \text{spatial frequency} \]
\[ M_{\infty} = \text{free stream Mach number} \]
\[ p_{\infty} = \text{free stream pressure} \]
\[ q = \text{dynamic pressure} \]

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\( R_{xx} \) = autocorrelation function
\( S \) = cross-spectrum
\( U_\infty \) = free stream velocity
\( \rho_\infty \) = free stream density
\( \phi \) = phase
\(<…>\) = time average

I. Introduction

LATFORMS at high subsonic Mach numbers introduce aero-optic disturbances caused when free shear layers are produced beyond flow separation. These generate large vortices with spatially complex density fluctuations. The resulting index of refraction fluctuations also vary rapidly, making compensation difficult. The requirements and performance benefits in compensating for aero-optical effects depends on the accuracy of the flow physics model from which wavefront distortion is derived. The approach in this study is to use computational fluid dynamics (CFD) to determine the time-dependent, three-dimensional flow solution for density and pressure, and integrate the solution along each line-of-sight (LOS) through the flow to determine the two-dimensional optical path difference (OPD) or wavefront error (WFE). Prior to this effort, no CFD code had been validated on a one-to-one wind tunnel scale while using optical figures-of-merit (FOMs). In the past, model accuracy was limited to “verification” of trends, based on scaling arguments for optical FOMs and correlation of fluid mechanical properties such as pressure and velocity. A high accuracy CFD-based model can provide detailed insight into the aero-optic disturbances caused and enable mitigations strategies.

II. Approach

A four step approach was utilized to validate the CFD-based model. The first step was to establish flow conditions, determine the required scale size and identify the measurements to be obtained. The second step was to construct the experimental apparatus and obtain the required measurements. During this phase upgrades were made to existing wavefront sensor systems and a 12-inch diameter hemisphere-on-cylinder turret was developed for use during the wind tunnel testing. The turret was then integrated with the wind tunnel, along with the wavefront sensor (WFS) system. The wind tunnel tests were then conducted, starting with characterization of the fluid mechanical properties of the flow, followed by optical properties of the wavefront at various flow speeds and LOS angles to obtain required measurements. The third step was to model the flow using the CFD code and calculate the OPD along each line of sight where measurements were obtained. Input to the code includes the 3D computational grid defining surface boundaries of the turret and wind tunnel walls, and inlet flow profile. The steady and unsteady numerical solution for density, pressure and Mach number were then calculated. Then the optical path length along each line-of-sight was calculated and the piston, tilts, and inviscid flow static phase were removed to yield OPD. The last step of the process was to compare the OPD and in-flow phase correlation length statistics between the wind tunnel measurement and model calculations, as a function of LOS angle. Appropriate changes to the flow physics were then made to improve agreement between the measured and modeled results.

III. Wind Tunnel and Optical Measurements

The experiments were conducted in the subsonic wind tunnel at the US Air Force Academy, Colorado Springs, CO (elevation 7200 ft above sea level). The tunnel has a 3 ft x 3 ft x 8 ft test section, as shown in Figure 1. Mach numbers in the test ranged from M0.35 to M0.45.

Figure 2 shows the configuration of the optical turret. The turret is composed of a 12-inch diameter sphere mated to a cylindrical base. The hollow sphere is fitted with a flush-mounted convex lens with an outer radius of curvature conforming to the curvature of the sphere. The sphere can be rotated along a vertical axis allowing variation in elevation angle between 40° and 140°. The cylindrical base, mounted and sealed on a flat plate, can be rotated to any azimuth angle. Sealing the base ensures that the interior of the beam director is nominally at the test-section static pressure.

The turret is mounted on the back interior wall of the wind tunnel, as shown in Figure 3. Turret location and test section dimensions are shown in Figure 4. The turret is 54 inches downstream from the beginning of the test section.
Figures 5 and 6 show the turret coordinate system used to define the location of the pressure and velocity sensors. The turret has ten static pressure ports and four Kulite unsteady pressure sensors (two mounted on the turret and two on the mounting plate downstream of the turret). Profiles of the streamwise velocity in the direction normal to the mounting plate (z-direction) were measured. The Kulite sample rate was 100 kHz with a low-pass cut-off at 40 kHz. Figure 6 shows the velocity profile of the incoming boundary layer upstream of the turret, for sensor #1 located upstream. The thickness of the boundary layer is approximately 2 to 2.5 cm. This is consistent with boundary layer measurements conducted in the wind tunnel using a static pressure rake.

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The first of the optical measurements were 2-D wavefronts across the aperture, uncorrelated in time (10 Hz), measured using a Wavefront Sciences CLAS-2D Hartmann wavefront sensor system. The optical system configuration is shown in Figure 7.

A frequency-doubled YAG:Nd laser beam (6 nsec pulse duration) was expanded to a 5-inch diameter collimated beam, and directed from the optical bench to the test section and turret using two 8-inch flats. The return beam from inside the turret was separated using a cube beamsplitter. The WFE was measured using a 2-D Shack-Hartmann wavefront sensor with a 24 x 36 subaperture lenslet-array. Two hundred wavefronts were recorded at each elevation angle and Mach number. To minimize the higher-order WFE at the edge of the pupil in the beam expansion optics, only the 4.5-inch diameter central portion was used to calculate wavefront error.

Figure 7. Integration of Hartmann WFS with wind tunnel test section and relay optics.

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Figure 8. Selected wavefront realizations at 76°, 90° and 132°. M = 0.4 flow is from left to right.
The Hartmann WFS data at each elevation angle and Mach number were post-processed as follows (1) A reference "no-flow" wavefront was obtained at the beginning of each run to characterize the static, no-flow aberrations imposed on the laser wavefront. This provided a reference from which to estimate deviations due to flow (2) The piston and tip/tilt components were removed from each wavefront. The tip/tilt was recorded and mean value calculated (3) A “steady-state” or DC component wavefront was computed by averaging the piston/tip/tilt-removed wavefronts in the previous step (4) The steady wavefront was subtracted from each wavefront in the ensemble, and rms OPD calculated (5) The average rms OPD was calculated for the ensemble. Figure 8 shows selected wavefronts measured at 76°, 90° and 132°, with some prominent features noted.

IV. CFD Setup

A multi-zone grid system was generated for the flow computation. The geometry was based on a CAD drawing looking downstream into the test section, as in Figure 4. Figure 9 shows the resulting zones and computational domain. It extends 45 inches upstream of the turret center to 150 inches downstream. A total of 2.7 million nodes divided into 52 zones were used. Figure 10 shows half of the O-type computational grid in the vicinity of the turret. The blue grid represents the turret surface. The black grid defines the tunnel wall used as the base plane. The red grid represents the central flow plane. To avoid degenerated cells at the top center of the turret, a separate zone was added. The grid nodes were clustered near the turret surface and tunnel walls for the boundary layers. Grid cells were also clustered in the streamwise direction towards the downstream side of the turret where separated shear layers were expected.

The flow solver uses a finite-volume technique with multi-zone method to solve generalized multi-dimensional flow in a body-fitted grid system. The blending of density- and pressure-based numerical methodology in the code allows efficient computation of both compressible and incompressible flow regimes. For time-accurate calculations, dual-time stepping was used. For turbulent flow computations, the Partially-Averaged Navier-Stokes (PANS) technique was implemented in the k-ε model. The PANS method uses two resolution control parameters with filtering of the flow variables. In the traditional Reynolds-averaged Navier-Stokes (RANS) equations, turbulence is not resolved but modeled to add turbulence effects to the mean flow. In the PANS model, parameters are used to limit the unresolved scales to those smaller than the grid size. The approach is similar to that used in Large Eddy Simulation (LES). The difference is that LES uses wave number as the filter, while the PANS model filter uses turbulent kinetic energy and dissipation. The PANS parameters, ftk and fte, are defined as the ratios of the unresolved to the total turbulence kinetic energy and dissipation, respectively. Values range between 0 and 1. The smaller the value, the less turbulence scales are modeled and thus, more directly computed. At the limit, a value of zero turns off the turbulence model and solves like a Direct Numerical Simulation (DNS). At the other limit, a value of one imposes a RANS model.

In theory, the parameters ftk and fte are functions of grid size, and the distributions of total kinetic energy and dissipation. To simplify implementation in Phase I, constant ftk and fte values were used throughout the computational domain. In Phase II, the parameters were left as field variables varying from point-to-point. For the problem to remain computationally tractable, however, only two values of ftk were specified - one in free stream conditions.
(ftk₁) and the other at the viscous surface (ftk₂). A smoothing function was then applied between the two to avoid discontinuities. To further simplify the problem, fte was set to 1.0 for all cases in which flow Reynolds numbers were high and turbulence dissipation scales not resolved.

The Mach 0.4 dataset was used as the basis for validating the CFD model. At the wind tunnel altitude of 7160 ft (2.18 km), the M0.4 inflow velocity corresponds to 137 m/sec, with density 0.99 kg/m³. The corresponding Reynolds number is 2.9E6. To simulate the boundary layer, the inflow condition was fitted with a profile scaled from the wind tunnel boundary layer experimental survey [1]. Data at the X = -27 inch plane was scaled to the desired plane at X = -45 inches, assuming an X² thickness growth rate. The measured and scaled profiles showed excellent agreement.

The unsteady nature of the turret flow requires time-dependent computation. However, a steady-state flow computation is done first to provide an initial condition for the unsteady flow computation. When the computation is switched to time-dependent, an induction period is required for the flow solution to transition to the unsteady solution. The time-accurate flow computation requires a small time increment to converge in each step. In this analysis, the highest frequency is about 2000 Hz, or a period of 500 µs. To ensure accuracy, 5 µs time steps were selected. Each case was run for more than 5000 steps (25 ms total duration) before data collection. Solutions were saved at 50 µs intervals. A total duration of 15 ms (300 frames) of data was stored for the wavefront statistics supporting validation.

As mentioned, the upgraded PANS model uses two ftk parameters. Figure 11 shows the distribution of ftk₁ (freestream) and ftk₂ (wall or boundary) in the flowfield. If the two values are the same, ftk is constant throughout the domain. If they vary, there is a smooth transition. A number of ftk pairs were traded to evaluate effects to determine the combination satisfying both required flow features and separation point. Results of ftk = ftk₁ ~ ftk₂ = 0.4 ~ 1.0 (Case 1) and ftk = 0.5 (Case 2) are reported. In Case 2, the PANS model is equivalent to that used in Phase I. The approach also serves to verify the usefulness of the PANS upgrade.

![Figure 11. Example of ftk distributions about turret.](image)

**V. Comparison of Flow Solutions and Fluid Measurements**

An instantaneous realization of the pressure contour in two perpendicular plane sections for Case 1 and Case 2, are shown in Figure 12. The left plot in each is a vertical section through the central Y = 0 plane. The right plot is a horizontal section through the shoulder (Z = 4.5 inches) plane. The low pressure region behind the turret is a result of the large wake. In the left figures, a low pressure circular area forward of the turret base is the core of the horseshoe (or necklace) vortex. At 100° to 110° from the forward stagnation point, the flow separates from the surface and a shear layer starts to form. The instability in the shear layer causes the flow to roll into vortices. When viewed as a function of time at 1000 samples (or frames) per second, the pressure within the vortices exhibits the oscillatory behavior observed in particle image velocimetry (PIV). This is the most distinctive, prominent feature critical to an accurate simulation of the aero-optical effect. The two perpendicular views show a significant number of vortices formed aft of the cylindrical base and dome. More vortices appear in Case 2 compared to Case 1.
Figures 13 and 14 compare the velocity profile measurements with those extracted from flow solutions at locations 1 and 5, respectively. The hot-wire locations are defined in Figure 6. The red and green curves represent Case 1 and Case 2 results, respectively, and blue points represent measurements. The magnitude of the velocity was calculated using only U and W components because the hot-wire was parallel to the Y-axis in the wind tunnel. The mean velocity is shown on the left in each figure, and the rms fluctuation on the right. Both are normalized with respect to the inflow conditions because M0.35 data were used at locations 3 to 5, where no M0.4 data were available. The vertical axis is the distance from the base plane (Z) normalized to the turret height (H) of 10.5 inches.

At Location 1, 17 inches upstream of the turret center, both solutions show a boundary layer profile characteristic of a flat plate. The Case 1 profile shows a boundary layer thickness of Z/H = 0.1 that matches test data. Case 2 has a thinner boundary layer with a thickness of only 0.07. The RMS values for both test and computation are very low as expected in a flat plate flow. Location 5 (Figure 14) is downstream of the turret in the middle of the wake. The wake in Case 1 is almost closed.

Figure 15 shows the time-averaged pressure coefficient (C_P) as a function of overhead elevation angle. 0° is at the forward stagnation point. The pressure drops along the streamline on the windward side and recovers on the leeward side until flow separates. A wake is formed after separation, with pressure fluctuating around the separation pressure. The test data show the separation point at ~ 115°. The CFD analysis shows separation at 110° and 100° for Cases 1 and 2, respectively. The error in the prediction angle is a result of the PANS model. The Case 1 prediction is closer due to the use of full RANS (ftk = 1.0) inside the boundary layer.
VI. Optical Path Difference

The optical path difference (OPD), or wavefront error (WFE), in the CFD analysis is based on sampling the flow solution over an array of “beamlets,” as shown in Figure 16. The parallelepiped close-packed array is co-aligned with the line-of-sight (LOS). A 25 x 25 beam grid extends from inside the turret to the wind tunnel wall. The flow density field is interpolated to the beam grid for each solution frame. The density is integrated along each ray and converted to index. Average optical path length, or piston, is removed from the array, leaving the OPD.

Figures 17 and 18 show instantaneous realizations of the tilt-removed OPD maps at 120° and 132° for Cases 1 and 2, respectively. These are the CFD equivalent of the measured reconstructed wavefronts in Figure 8. Although direct comparison of the random realizations in time is not possible, characteristic scales in the wavefronts at 132° are similar. As expected from the flow solution, Case 1 produces a smaller OPD than Case 2.

![Figure 16. Beamlet array (left) for OPD modeling and defining LOS (right).](image)

![Figure 17. Case 1 tilt-removed OPD realization at 120° and 132°.](image)

![Figure 18. Case 2 tilt-removed OPD realization at 120° and 132°.](image)
VII. Wind Tunnel and CFD Based Comparison

Two figures-of-merit (FOMs) are used to compare the wind tunnel and CFD-based wavefronts for validation. The first is rms wavefront error, defined as the ensemble- (or time-) and aperture-averaged wavefront standard deviation with piston and tilt removed

\[
\text{RMS OPD, } \sigma_{\text{rms}} = \left[ \langle \sum_{\phi^2(r,t)} - \langle \phi(r,t) \rangle^2 \rangle \right]^{1/2}
\]

Where \( \langle \ldots \rangle \) denotes time average, and \( \langle \ldots \rangle = \text{expectation value} = \int \int \phi(r,t) \, dr / \int \int dr. \)

In this analysis, the OPD is calculated over the central 4.5 inches of the 5-inch diameter beam.

The second FOM is the ensemble-averaged phase correlation length \( L_c \) based on the first zero crossing of the autocorrelation \( R_{\phi\phi}(\Delta r) \) of the phase in the flow direction:

\[
R_{\phi\phi}(\Delta r) = \frac{\langle \phi(r,t) \phi(r+\Delta r,t) \rangle}{\langle \phi^2(r,t) \rangle}
\]

The probability density functions (PDFs) for the M0.4 2D Hartmann (blue) and CFD-based (red) OPDs are shown in Figure 19. Figure 20 shows the mean values as a function of elevation angle. The PDFs are based on 300 samples at each angle. The same algorithm is used to calculate the OPDs in the wind tunnel and CFD-based datasets. The results show reasonable agreement throughout the elevation range. Also shown in Figure 20, in the shaded area, is the expected trend in OPD for two limiting cases. The lower limit in the shaded area assumes an increase in OPD based on a \( 1/\sin \theta_{\text{elev}} \) factor for a turbulent shear layer with constant thickness. This is the OPD due to increased angle of incidence at the shear layer. The upper limit assumes both an increase due to angle of incidence, and a \( 10^\circ \) divergence of the shear layer. Ten degrees was estimated from the CFD-based flow solution. The two limits fall between the wind tunnel measurement and CFD estimates. Thus, not only do the measurements and model agree in both absolute and relative senses, but they are consistent with behavior of the flow.

Figure 19. OPD probability density functions for 2D WFS measurements (blue) and CFD model (red,Case2) for elevation angles of 60°, 76°, 90°, 103°, 120°, and 132°.
PDFs were calculated in a similar manner for the phase correlation length. Again, the same correlation function algorithm was used on the wind tunnel Hartmann and CFD-based data, and criterion used to define correlation length. The PDFs as a function of elevation angle are shown in Figure 21. Agreement between measurement and model is excellent. Figure 22 shows the mean values and standard deviation of the correlation length as a function of elevation angle. As with OPD, the PDFs are based on 200 to 300 samples at each angle and the same algorithm is used to calculate the correlation lengths in each dataset. Note that the correlation length does not change much with elevation angle. The viewing aspect due to the LOS results in a shortening of the correlation length (~sin θelev) as the elevation angle increases beyond 90°. However, scale lengths are known to increase with elevation. This can be seen in the pressure contours generated in the flow solution. It appears that the two effects nearly cancel over the elevation range and flow conditions. The consistency between the CFD-based model and measurements supports this conclusion.

![Figure 20](image1.png)

**Figure 20.** Mean and standard deviation of OPD for wind tunnel measurements (blue) and CFD (red, Case 2) model.

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![Figure 21](image2.png)

**Figure 21.** OPD probability density functions for 2D WFS measurements (blue) and CFD model (red, Case 2) for elevation angles of 60°, 76°, 90°, 103°, 120°, and 132°.
VIII. Summary & Conclusions

A CFD-based aero-optics phase model has been validated using wavefront sensor measurements in a subsonic wind tunnel. The model was based on as close a simulation as possible to the actual wind tunnel configuration and flow conditions including full-scale turret and test section dimensions, inlet flow profile, and tunnel wall effects.

After developing the system requirements, establishing the trade space, and defining the figures-of-merit (FOM), a 12-inch diameter optical turret was designed and fabricated. The optical beam train for the wavefront sensor was also developed. In parallel with the hardware, the limitations of the CFD code were identified and appropriate updates made to the flow physics to properly model spatial and temporal frequency characteristics, including necklace vortex structure and separation point location.

In retrospect, the FOMs were probably overly-conservative because they required direct comparison of both the magnitude of the aero-optics only wavefront error and in-flow phase correlation length. This is in contrast to Strehl and power-in-a-bucket which are not unique with respect to spatial frequency content and OPD, especially in a systems context. In the latter, phase errors may add coherently and thus “hide” the effects of specific contributions. In this analysis, validation of the flow physics alone was accomplished.

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