Computational methods to compute wavefront error due to aero-optic effects

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ABSTRACT

Aero-optic effects can have deleterious effects on high performance airborne optical sensors that must view through turbulent flow fields created by the aerodynamic effects of windows and domes. Evaluating aero-optic effects early in the program during the design stages allows mitigation strategies and optical system design trades to be performed to optimize system performance. This necessitates a computationally efficient means to evaluate the impact of aero-optic effects such that the resulting dynamic pointing errors and wavefront distortions due to the spatially and temporally varying flow field can be minimized or corrected. To this end, an aero-optic analysis capability was developed within the commercial software SigFit that couples CFD results with optical design tools. SigFit reads the CFD generated density profile using the CGNS file format. OPD maps are then created by converting the three-dimensional density field into an index of refraction field and then integrating along specified paths to compute OPD errors across the optical field. The OPD maps may be evaluated directly against system requirements or imported into commercial optical design software including Zemax® and Code V® for a more detailed assessment of the impact on optical performance from which design trades may be performed.

Keywords: aero-optic effects, integrated modeling, computational fluid dynamics, optical path difference, airborne, windows, domes, turbulent flow, wavefront error

1.0 INTRODUCTION

The generation of near-field index of refraction variations in the air by aircraft induced turbulence or local thermal gradients leads to wavefront or optical path difference (OPD). These variations degrade the performance of imaging and optical communications sensors (Figure 1). Flow features that create this phenomenon include boundary layers formed on the fuselage and wings, vertical structures shed from turrets and pods, and thermal variations from engine exhaust. OPD results obtained via simulation or testing have proven to be of high enough quality to be valuable in predicting the impact of near-field index variations on optical performance. However, the cost and time associated with both these methods inhibit their use during the design stages of a program, particularly where a matrix of design tradeoffs exist and rapid turnaround is required.

Recent advances have enabled more rapid computation of OPD due to near-field refractive index variations. First, the combination of ever increasing computing capabilities coupled with the development of the large eddy simulation (LES) class of turbulence models, as implemented by commercial computational fluid dynamics (CFD) codes, have improved the practicality of employing CFD analysis techniques to efficiently resolve near-field flow characteristics. Second, commercial software tools have been developed that create OPD maps via integration along optical rays through three-dimensional data for direct input into commercial optical design software. These developments have been combined to create an efficient and accurate process to quantitatively assess broad design spaces and complex geometries during the early conceptual design phases of programs[1]. The details of this process are discussed within.

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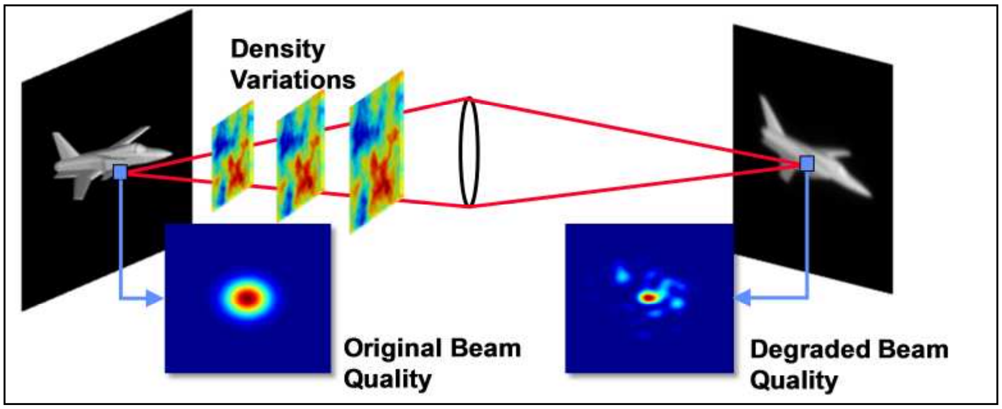

Figure 1: Impact of Air Density Variations on Optical System Performance

2.0 IMPLEMENTATION

The aero-optic analyses described in this paper are embedded in the general purpose optomechanical analysis software program SigFit[2]. The most common use of SigFit is to analyze finite element derived optical surface deformations. Deformations are typically fit to polynomials for enhanced interpretation by the mechanical engineer in the design development of an optical mount or formatted into various optical surface types to be represented directly into optical design software for detailed optical performance assessment. SigFit also performs mechanical analyses of adaptive optical systems to predict the correctability of systems and optimize adaptive solutions including actuator layouts, actuator type, and the actuated shape of the optical element. With a ray-trace capability, SigFit offers capabilities to perform line-of-sight analyses for optical systems. Thermo-optic[3] and stress birefringence effects are assessed using SigFit's bulk optical property algorithms that utilize three-dimensional temperature and stress fields and convert them into optical degradation errors including wavefront and polarization. The aero-optic analysis approach discussed in the next section is similar to the existing thermo-optic analysis as shown in Figure 2.

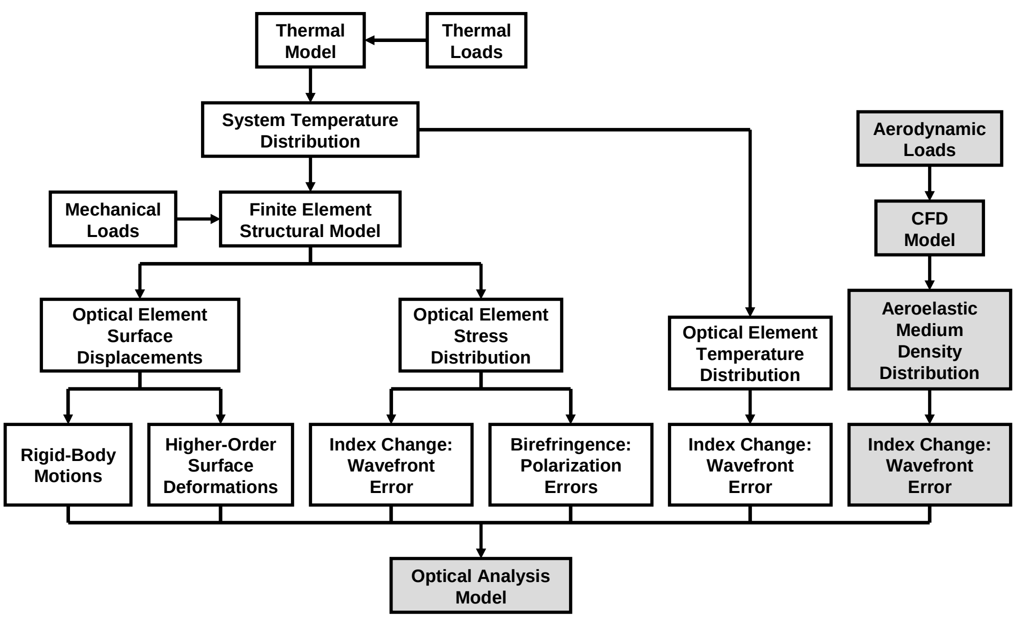

Figure 2: Integrated optomechanical analysis flow

2.1 Current OPD solution

For a transmissive optic analyzed with a finite element heat transfer analysis, temperatures are provided at all of the lens nodes. SigFit will read the lens nodes, elements, and temperatures, and then integrate through the lens to determine the integrated optical path difference due to index change with temperature. The OPD is the change in optical path length (OPL) through the nominal lens as given in Equation 1. When the temperature in the lens changes, the index also changes, causing an optical path difference. In general, the coefficient (dn/dT) may be temperature dependent.

$$OPD = OPL_{Disturbed} - OPL_{Nominal} = \int_{s1}^{s2}\left(n + \frac{dn}{dT}\Delta T\right)ds - \int_{s1}^{s2} nds = \int_{s1}^{s2}\frac{dn}{dT}\Delta T ds = \sum_j \frac{dn}{dT}_j \Delta T_j \Delta s_j$$

SigFit numerically integrates along paths through the lens as shown in Figure 3. At each integration point (circles), the temperature is determined from the nodes on the corners of the enclosing finite element using shape functions for that element. In this way, the shape functions used to derive the element are used to post-process the results. The user specifies the number of integration points along an integration path. The resulting OPD of a given path is assigned to the node on the entrance surface. The resulting OPD map over the full surface is then passed to an optical code as a set of polynomials or interpolated to a rectangular grid array.

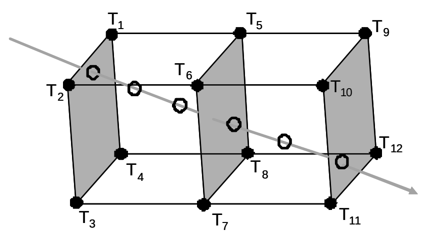

Figure 3: Integration path

The approximation in the OPD approach arises from the fact that the integration paths are not developed by a real ray trace and cannot represent the effects due to multiple field points. The true rays may not match the integration paths. To obtain more accurate solutions, SigFit supports the gradient index feature in CodeV using a DLL. As CodeV traces rays through the gradient index lens, it provides a current ray point location to SigFit. SigFit returns the optical index and index gradient at the point, updated for the temperature field. The DLL approach is more accurate, but also slower computationally.

2.2 Extension to aero-optic analysis

The overall approach to aero-optic analysis is generally similar to the thermo-optic analysis described above, except for changes required for extremely large models. The refractive index of an aeroelastic medium, such as air, varies with density similar to the variation of refractive index in glasses with temperature. The index of refraction (*n*) is related to the air density (*ρ*) by the Gladstone-Dale relation (Eq. 2). Therefore, by computing the density field surrounding an optical system it is possible to develop relationships that describe aero-optical effects.

$$n = 1 + K_{GD}\rho$$

SigFit reads the density profile results of the aeroelastic medium from a CGNS file generated from computational flow dynamics (CFD) analysis. SigFit then integrates (Eq. 3) through the aeroelastic density profile along specified paths to calculate an optical path difference (OPD) map. The resulting OPD map is then fit with polynomials or interpolated to a rectangular array for input to an optical analysis program. SigFit provides data post-processing that allows removal of the spatial average, tilt, and focus terms to visualize the higher-order OPD variations and to better evaluate impact on system performance. The OPD maps may be evaluated directly against system requirements or imported into commercial optical design software including Zemax® and Code V® for a more detailed assessment of the impact on optical performance.

$$OPD = OPL_{Disturbed} - OPL_{Nominal} = \sum_j \frac{dn}{d\rho}_j \Delta\rho_j \Delta s_j = \sum_j K_{GD} \Delta\rho_j \Delta s_j$$

2.3 CGNS Interface

The CFD General Notation System (CGNS) is a set of standards, together with software implementing those standards, for the recording of data associated with Computational Fluid Dynamics (CFD). Two types of model meshes are supported in CGNS: unstructured and structured. A subset of the structured mesh is the Chimera or overset meshes used in OVERFLOW. The unstructured mesh is typical of any finite element (FE) mesh where elements have any shape and size, but do not contain any regions in which the mesh overlaps itself. ANSYS Fluent, for example, utilizes both structured and unstructured mesh types but does not allow overset grids. The overset structured meshes may overlap one another, and a separate file includes the cell blanking information, instructing which mesh should be used in such overlapping regions. During development of SigFit's aero-optic capability the existing FE interfaces were useable for unstructured meshes, but overset meshes required additional program development. The example in the next section shows overset meshes.

In detailed CFD analyses of turbulent air flow, the model may contain millions of nodes and elements. The existing element interpolation approach has excessive run times when applied to such models. Therefore, a three dimensional closest node interpolation was added to SigFit to shorten the run times. The user may specify how many closest nodes to use in the interpolation, typically three to eight. In the CGNS file the desired elements are referenced by their zone number or a user specified component name. For CFD models which are similar in size to structural/thermal lens models (typically tens of thousands of nodes, rather than millions), the existing element interpolation is still available.

Typically only a small portion of the full CGNS model will be included in the ray path calculations and the user can select that subset by placing geometric bounds on the nodes to be included in the analysis as a "lens". Efficiency is enhanced by breaking the reduced volume into a user specified number of cells for the closest node search algorithm. In addition, the time-dependent nature of the fluctuating aero-optic analysis requires the saving of many snapshots of the solution. To facilitate postprocessing, SigFit was modified to read multiple CGNS input files so multiple time steps could be processed in a single execution of SigFit.

2.4 Demonstration example

The following small example was run as a demonstration problem. The flow over hemispherical dome was modeled using three structured overset meshes as shown in Figure 4 (cutaway view) with resulting density contours in Figure 5. Integration paths are shown in Figure 6. The user specifies a mesh which represents the entrance surface of the lens (dome) from which to start the integration paths and an exit surface (far field). The analysis could use existing surface meshes in the CGNS database if desired and appropriate. Otherwise, SigFit could create a user specified mesh on the surface of the dome and the far field as shown in Figure 6. The integrated OPD map due to the density field is given in Figure 7, where (a) is the total integrated OPD, and (b) has bias, tilt, and power removed. The plot in (b) represents wavefront distortion that cannot be corrected by pointing or focus shift. OPD results may be represented as a Zernike table in Figure 9 or a rectangular grid array (Figure 8) for importing to optical analysis programs. The grid array is useful for OPD maps with high spatial variations which are poorly represented by Zernike polynomials.

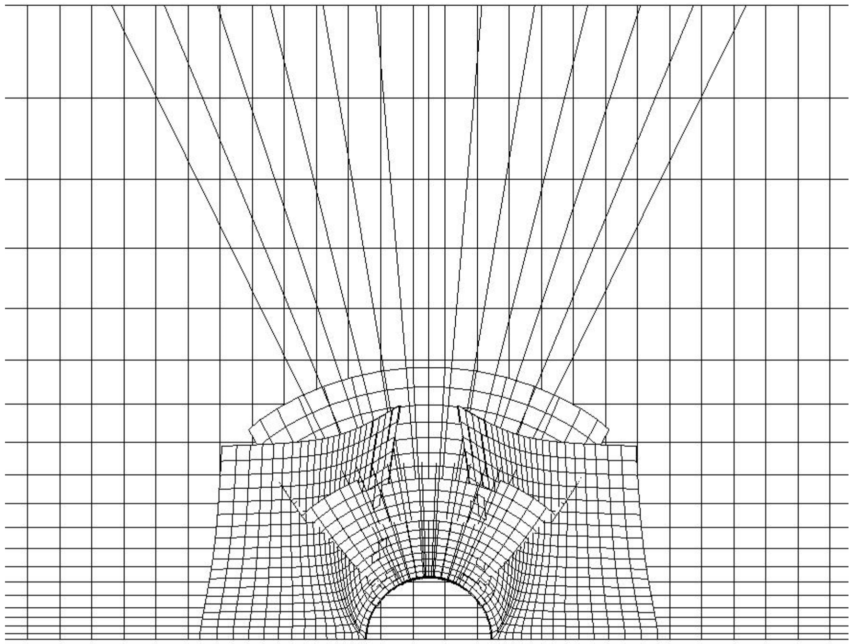

Figure 4: Cut-away view of three overset meshes and integration paths

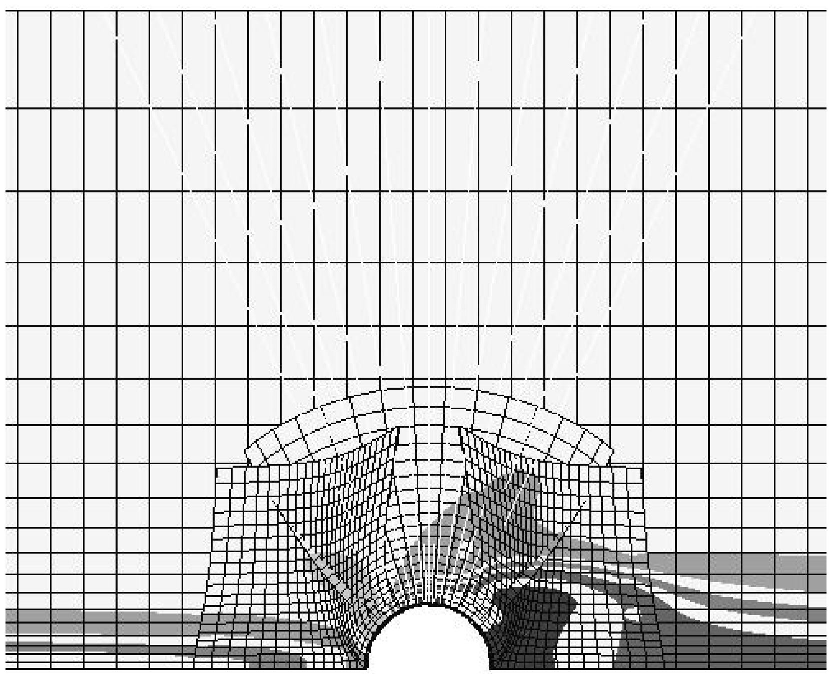

Figure 5: Density profiles due to flow over dome

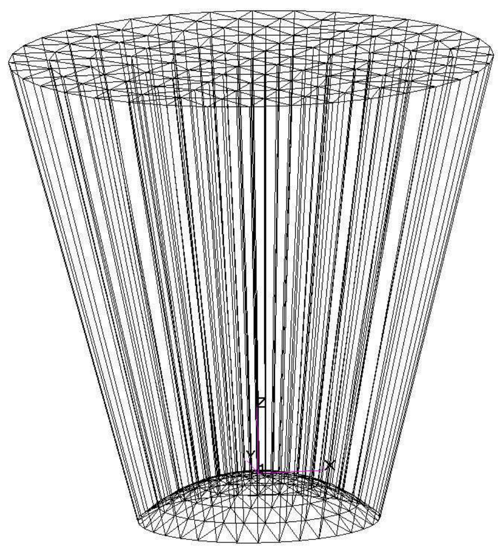

Figure 6: Dome and far field mesh with integration paths

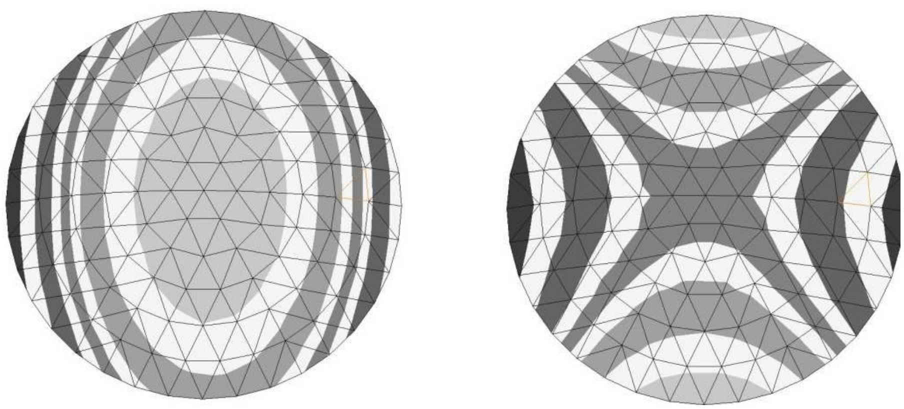

Figure 7: (a) integrated OPD map, (b) OPD with bias, tilt, power removed

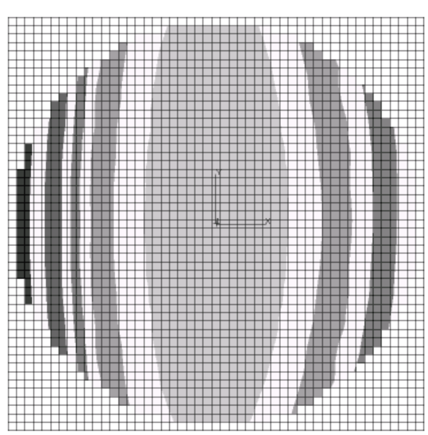

Figure 8: OPD interpolated to rectangular array

Order K	N	M	Aberration	Magnitude (Waves)	Phi (Deg)	Residual RMS	Residual P-V
			Input(wrt zero)			0.3801	0.0135
1	0	0	Bias	-0.03286	0.0	0.0395	0.0135
2	1	1	Tilt	0.00100	-10.2	0.0390	0.0125
3	2	0	Power (Defocus)	-0.00434	0.0	0.0202	0.0079
4	2	2	Pri Astigmatism	0.00381	89.4	0.0010	0.0006
5	3	1	Pri Coma	0.00012	16.0	0.0008	0.0004
6	3	3	Pri Trefoil	0.00005	7.1	0.0007	0.0003
7	4	0	Pri Spherical	-0.00002	0.0	0.0007	0.0003
8	4	2	Sec Astigmatism	0.00001	-15.6	0.0007	0.0003
9	4	4	Pri Tetrafoil	0.00012	0.7	0.0004	0.0002

Figure 9: Zernike fit to OPD map

3.0 APPLICATION

Expanding upon the demonstration example from the previous section, the hemisphere on cylinder style turret geometry (Figure 10) was used as a test case to validate the application of the aero-optics modifications within SigFit. This geometry is attractive because of its relative simplicity, the complex nature of the flow field it produces, and the benefit of numerous previous test cases provided in the open literature. The geometry modeled replicates a turret installed in the Air Force Academy 3 ft x 3 ft subsonic wind tunnel where experimental studies were conducted[4]. In addition, this geometry is a desirable platform for an optical beam director given the wide field of regard it provides and the ease of integration of an azimuth and elevation gimbal assembly.

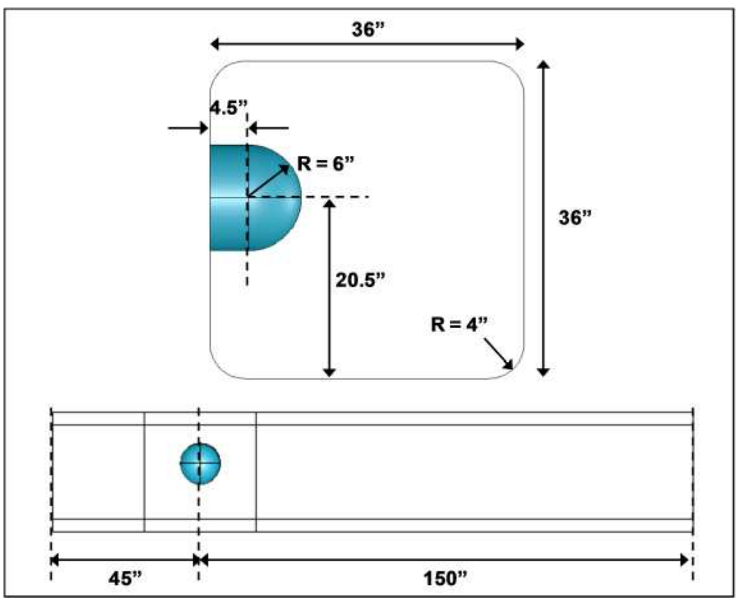

Figure 10: Hemisphere on cylinder turret test case geometry

A previous paper detailed more expansively the application of the aero-optics computation method developed for SigFit[1]. However, it is beneficial to review the basic fluid dynamic phenomenon which leads to the generation of time-varying index of refraction fields. The boundary layer upstream of the turret rolls up into the form of a horseshoe shaped vortex (Figure 11). This relatively steady feature has little impact for upstream viewing angles, but does play a role downstream in entraining higher momentum flow into the wake region as the vortex expands. The primary density and thus index variations are induced by the development of vortices within the unsteady wake in the aft region of the turret. These vortices have a lower pressure at their cores than the surrounding ambient pressure, leading to density variations. Rays that emanate from an aperture and project through this both spatial and temporal fluctuating field result in varying optical path lengths and thus distortion of the optical wave issuing into the far field. This impacts image quality if the unit is a visible sensor, or causes fluctuations of a projected beam decreasing its overall intensity on target as would be important for a high energy laser system.

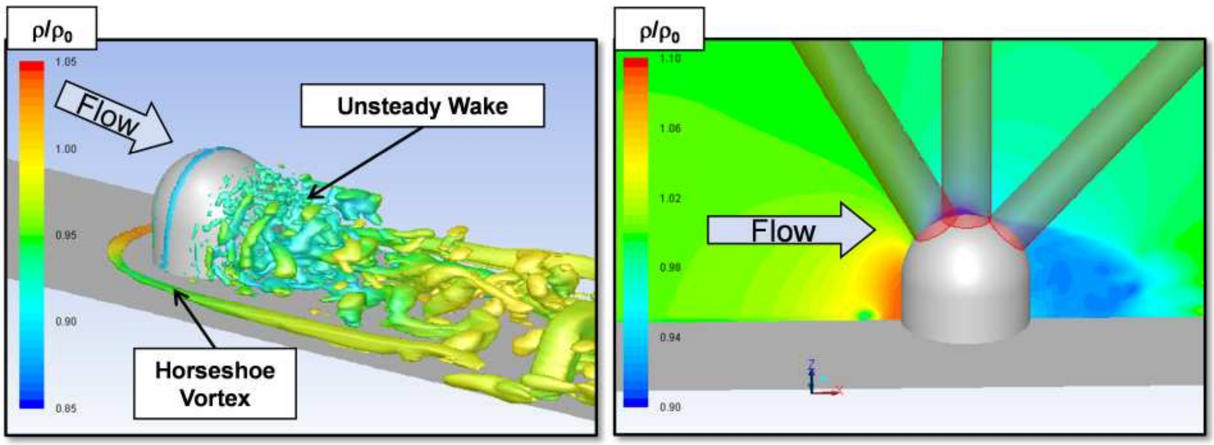

Figure 11: Snapshot of CFD results demonstrating the flow structures that lead to density and index variations

The CFD simulations are run until a statistically steady flow has developed, and then a series of snapshots of the flow are saved. These density fields were saved into the CGNS file format and the newly developed post-processing techniques developed for SigFit were used to calculate the OPD values and Zernike polynomials. The resulting normalized unsteady OPD values are accumulated for 300 different snapshots and the resulting RMS values plotted (Figure 12) against wind tunnel measurements[6]. The unsteady component of the OPD is determined by removal of the piston and tilt contributions as these terms tend to be more easily corrected using current active and/or adaptive optics systems. There does tend to be a range of scatter in the data based on the difficulty in the acquisition of such measurements and the inability to acquire data at all look angles of interest simultaneously. However, the SigFit results do appear to be within the right order of magnitude and capture the expected trends with look angle. Therefore, it is concluded that the modifications to SigFit that allow for the post-processing of time depending CFD simulation results is a valid approach as applied to this well documented test case.

4.0 SUMMARY

The integrated optomechanical analysis flow in SigFit (Figure 1) was expanded to include a general purpose aero-optic analysis capability. By using the CGNS database for the CFD results, the tool may be used with any CFD code that supports the CGNS database. The OPD effects of the density variations may be imported directly into a variety of optical analysis codes to predict optical performance degradation due to flow fields.

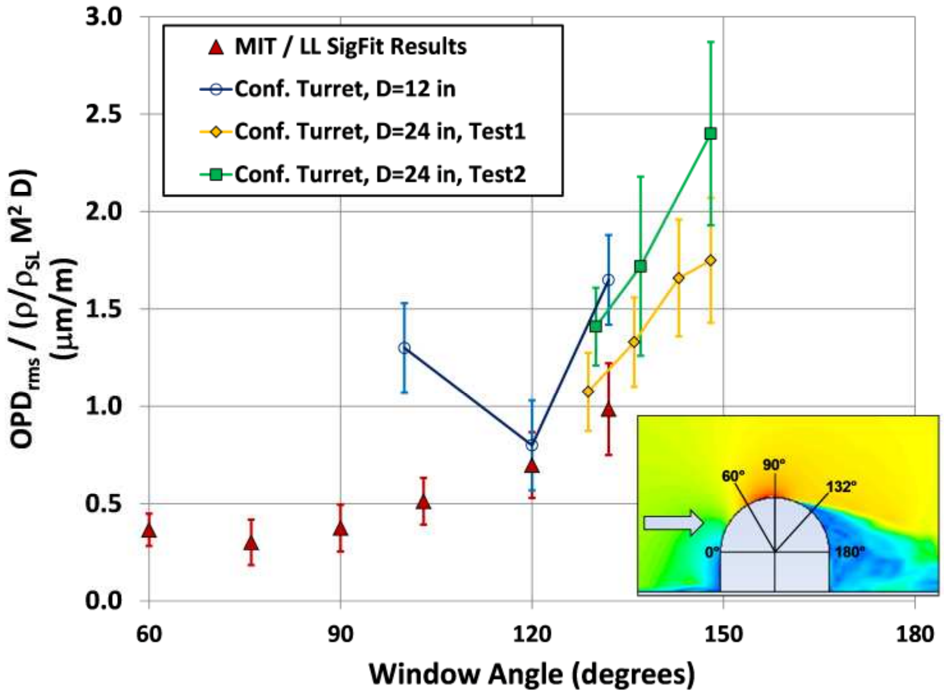

Figure 12: Normalized OPD-RMS compared to literature data[6]

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