WHITE PAPER

Mission-driven Optical Simulation of Thermal, Structural, and Turbulent Flow

There are some systems that engineers feel are so complex they cannot be simulated. Frequently, teams will turn to the much older and inefficient method of “build and break.” However, as people’s need for understanding these complex physics evolves, so must their tools. A more streamlined solution to complex design challenges is proposed. Demonstrating that simulation is not only possible, but also provides incredible accuracy as well as time and cost savings when compared to alternative methods.

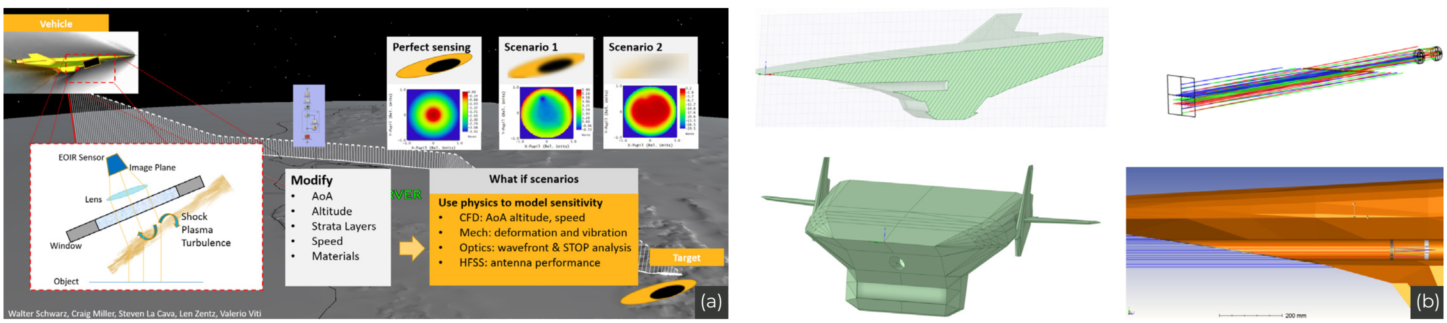

Figure 1. (a) Aircraft and optical system and performance results; (b) Aircraft and optical system.

Creating an optical system for high-speed aircraft or reentry vehicles entails consideration of numerous variables. The mission defines the strata layer flown, which in turn drives the species, or blend of gases flown through. The velocity and species determine the temperature change of both the vehicle and the surrounding gas mixture. Turbulent flow from varying pressure and temperature changes the gas’ index of refraction. At high speeds, this can lead to molecular separation or even plasmatic effects, which pose interesting problems for optical system design. In addition, friction from Earth’s atmosphere causes the heating of the vehicle and can lead to temperature variation in the optical elements in an asymmetrical way which changes the optical material’s index of refraction. The mounts also heat within the vehicle, and the resulting thermal expansion causes structural deformation to the optical elements. Finally, if the optical system is an infrared system, the heat of the components radiating the absorbed energy will result in narcissus effect, in which the components function as a source of light shining down the optical system like a flashlight.

With all that in mind for just a single application, it’s hard to blame designers and engineers for feeling overwhelmed at the challenges presented. Some of these problems can be solved through trial and error at the cost of significant budget and time. However, every element mentioned above can be simulated. Simulating complex systems early in the design and development phases can reduce the number of test flights required, provide design insights earlier in the product life cycle, and enable you to take action while still in the development phase, where greater changes are possible. Failure to include simulation early in the design cycle results in more costly prototyping and a greater number of test flights needed. If a critical issue is discovered later in the product design cycle, the options to resolve the issue are often limited and costly.

When approaching a multiphysics problem such as this, one major issue to overcome is the workflow employed. It is rare that a single tool, a single engineer, or even a single team has all the expertise required to accomplish such a task. However, a suite of tools that perform in concert across adjacent physics realms and facilitate seamless information exchange across engineers from different disciplines can help solve the problem more efficiently. Bridging the skill gap between experienced engineers and junior engineers is an additional benefit that comes from using a single software platform. With a workflow that allows for seamless exchange of information, automation of tedious and repetitive tasks is possible. Automation allows for a far more efficient use of engineering resources and has the added benefit of empowering a less experienced engineer to perform a complex analysis, all from a single interface. This allows more senior engineers or system-level engineers to set up the process and still ensure consistent results, even when less experienced engineers are performing the analysis.

The status quo workflow involves members from the optical team, the mechanical team, and the fluids team that work on their respective project aspects separately. After they complete their parts, they then hold meetings to try to understand the results. Hours are spent interpreting what a mechanical deflection or a flow field may mean by using spreadsheets and exported data tables. This type of workflow means that each discipline creates the designs separately, never simulating them together. To see how the effects work together, these teams will employ prototyping and testing to try and figure out how the system functions during use. This type of problem presents the ideal scenario where software is ideal to help solve. By performing a multiphysics simulation, this team can benefit from identifying any potential design and environmental issues far earlier in the design process – before the first prototype is built.

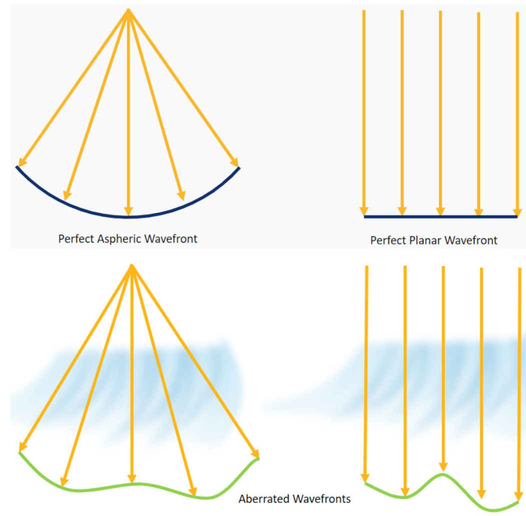

Figure 2. Ideal wavefront versus wavefront with aberrations from air.

A common strategy engineers use to solve multi-physics problems is to use a piecemeal approach whereby different tools are cobbled together to create a solution that works for the project. While this approach may be initially appealing and may solve the immediate problem, the frequent drawback is that these tools can become tedious to learn and maintain as operating systems and software requirements change. It can also be time-consuming to train new engineers to use the various tools that comprise the solution. Proprietary in-house tools or scripts can help but often lack sufficient documentation and lead engineers to often rely on a "tribal knowledge" method of dissemination thereby exacerbating the ramp-up time for a junior engineer. Companies and teams must also take into account the risk and related costs associated with custom code, such as adapting for future applications and maintenance issues such as bugs or instances where the tool's author leaves the company.

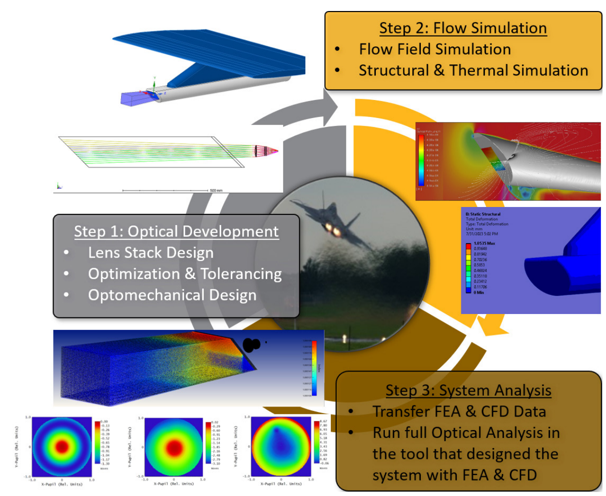

Figure 3. Aero-Optic Workflow.

Assessing the impact of structural and thermal effects on optical performance has been a standard practice for years. Structural, Thermal, Optical Performance (STOP) analysis describes a regiment where results of an FEA simulation are used to quantify the effects of structural and thermal changes on the optical performance of the system. However, STOP analysis does not consider the effects from fluids which, if left unaccounted for, can result in project failure. The situation extends beyond simply adding another step to the process due to inherent differences between finite element analysis (FEA) and computational fluid dynamics (CFD) such as simulation times, mesh shape, and mesh density. All of which culminates in a new dimension in an already difficult problem space.

A modern, streamlined alternative to convention is proposed Structural Optical Fluid Thermal (SOFT) analysis. To see how capable this workflow can be, take the example of a high-speed aircraft with a viewing window followed by an optical system behind the window. The mission-level data will define the strata layers or species of gas involved, and this will be the initial conditions for the CFD analysis. Once other flight variables such the aircraft's mechanics, flow field, temperatures, and pressures are considered, CFD data from Ansys Fluent will be used as the initial conditions for an FEA analysis in Ansys Mechanical. The temperatures and pressures from CFD will be used for the structural and thermal simulation, and this data will then be exported for analysis in Ansys Zemax OpticStudio.

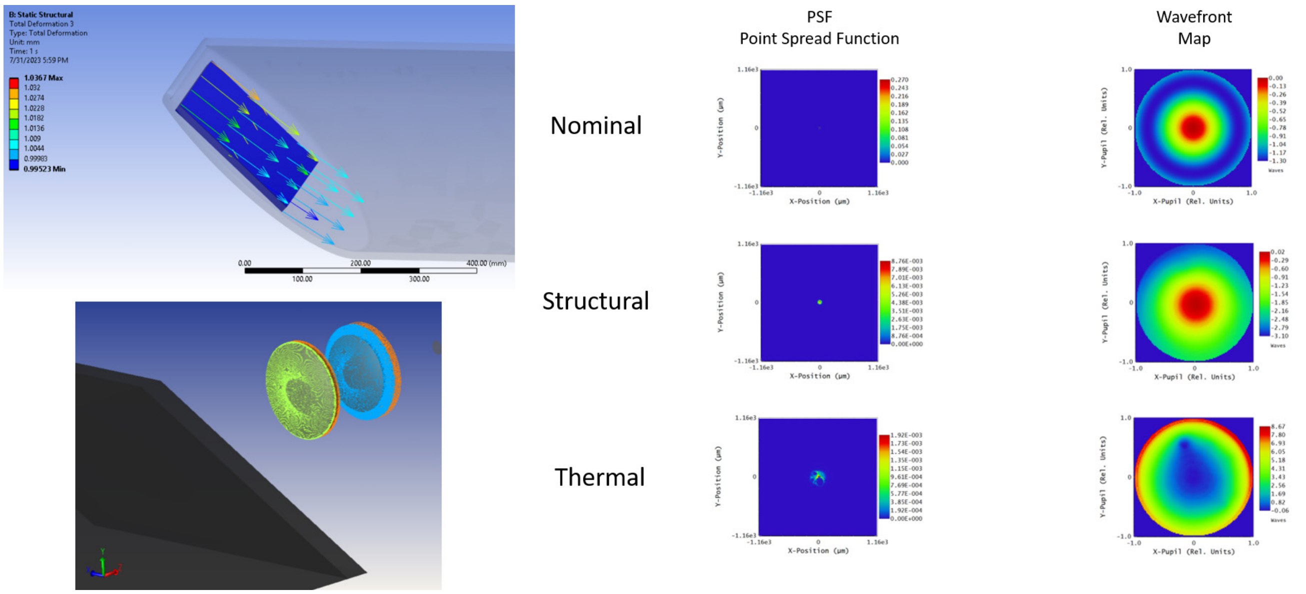

Figure 4. LEFT: Mechanical model of aero-optic system. CENTER: Comparison of nominal Point Spread Function and the effects of structural and thermal data. RIGHT: Comparison of nominal wavefront map and the effects of structual and thermal data.

New tools were developed to manage the information exchange between fluids and optics. On the CFD side, new functionality in Fluent allows for transient analysis of the flow field to be performed, then used to compute the optical path difference (OPD) and optical path length (OPL).

From the transient CFD analysis, a series of time steps are defined for transient system analysis. A new tool was created to complete the workflow between CFD tools and the optical effects of those fluids into Ansys Zemax OpticStudio.

Using point cloud data, which contains infinitesimally small points, the data can be provided from the nodal locations of a mesh or any other source as a means to extract physical quantities from a flow field using CFD. These points can then be translated into optical index of refraction for use in optical simulation.

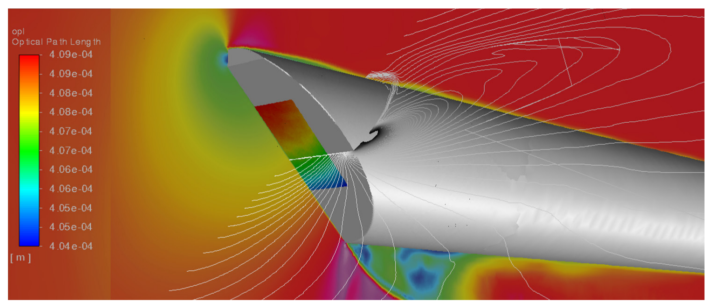

Figure 5. Modeling of Optical Pathlength CFD simulation.

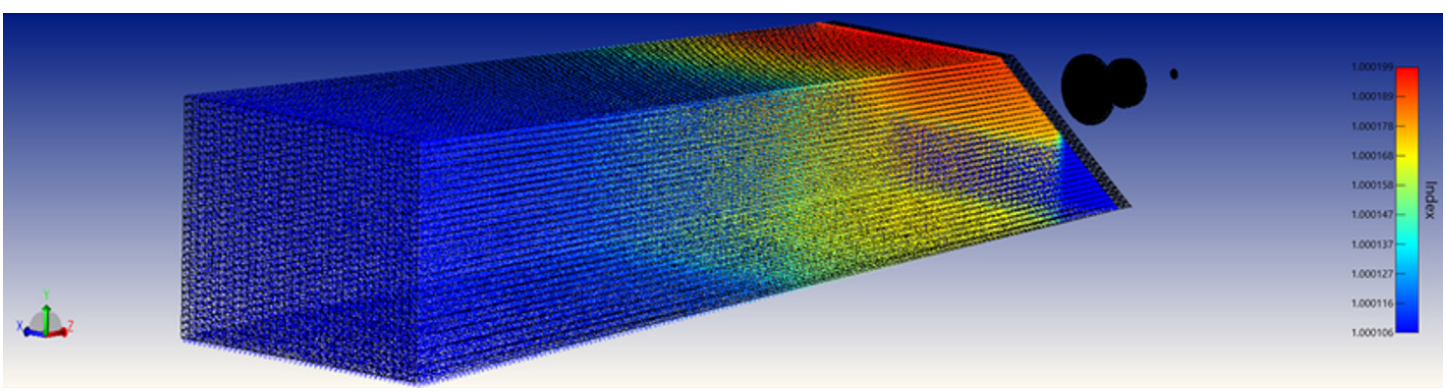

Figure 6. Refractive Index dataset from the flow field loaded into OpticStudio.

The point cloud method improves accuracy when compared to the typical methods currently in use: optical path difference (OPD), optical path length (OPL), and voxel methods, which use fixed volumetric spaces.

A fitting algorithm is used on the point cloud data which is comprised of infinitesimally small points. This allows for greater accuracy as it is only dependent on the number of points used and the mathematical fitting of the data. Other methods introduce additional sources of error, as they involve fitting to a known polynomial equation such as a Zernike or other optical surface type. The use of point cloud data as opposed to voxels is also more computationally efficient — and, with the help of proprietary algorithms, more accurate.

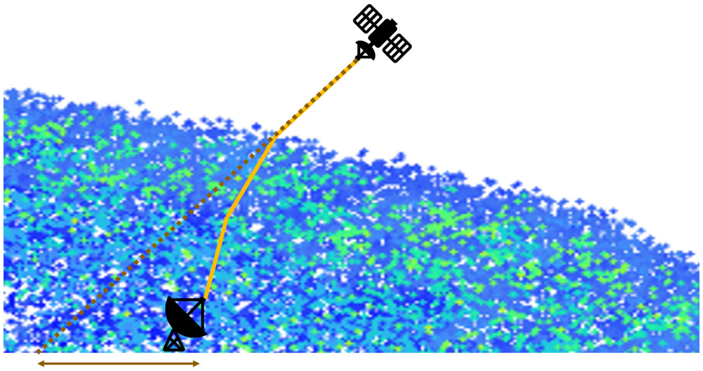

Figure 7. Example of aiming error resulting from refraction in the atmosphere.

Additionally, the point cloud approach enables you to consider the refraction of light. Some tools using OPD or OPL methods only account for phase and assume a perfect line of sight transmission of light without accounting for the bending or refraction of the light. The direct index method can account for refraction effects, which are critical for many applications.

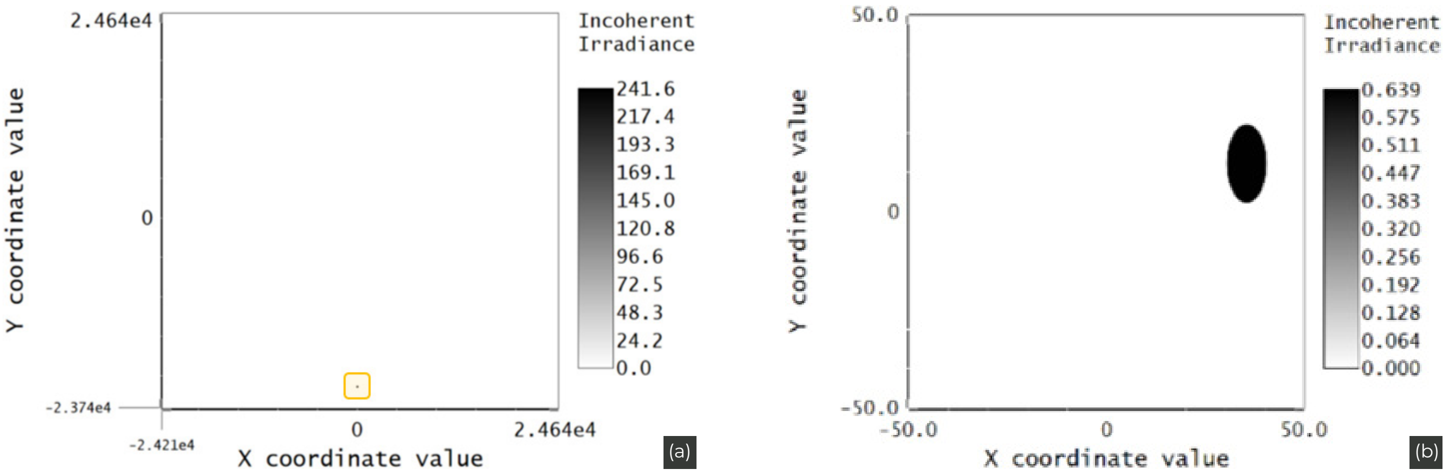

Figure 8. (a) Aiming error resulting from refraction effects; (b) Refraction effects on beam shape and aiming.

In addition to the new tools for processing data and improving workflow, new analytic tools were created to help understand what these multi-physics effects have on the optical system. Facilitating the ability to determine which effects are the largest issues and where in the system these issues occur.

This provides a huge advantage over any other method, as design errors can be simulated, tested, and corrected all in the early design stage prior to prototyping, testing, or flying the system. The use of simulation not only saves considerable amounts of money, but it also gives designers and engineers greater flexibility with any corrections that are needed since no tooling or production costs have yet occurred.

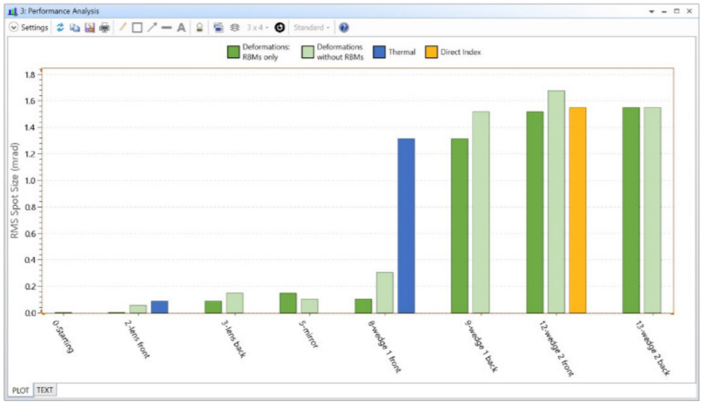

Figure 9. Performance analysis in OpticStudio demonstrates performance change at each surface and the physical phenomena that contributes to it.

The true power of SOFT analysis is that all CFD and FEA data flows back into the same optical software that created the nominal design. This means all metrics used to create the original design can be used to evaluate the simulated results.

Whichever criteria was used was used to benchmark the nominal design, MTF, wavefront error, spot size, or even image simulation, these same criteria can be run either with and without FEA and/or CFD data. Providing both a nominal benchmark and a simulated metric for comparison.

So far, we have looked at only an aero-optical example. However, it is worth noting that this workflow is robust enough to handle almost any fluid, structural, or thermal problem. A few we have identified include those in Figure 11.

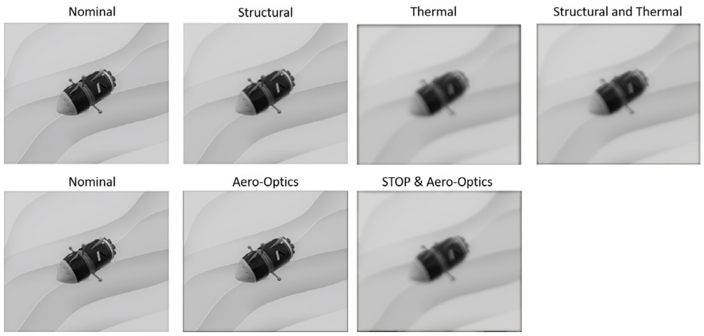

Figure 10. Image Simulation in OpticStudio makes it possible to readily interpret the physical effects on optical performance.

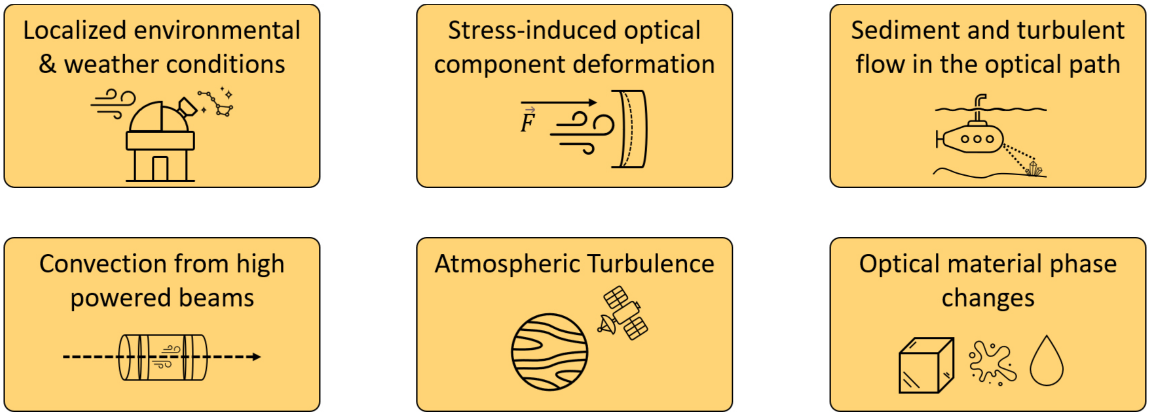

Figure 11. Examples of design challenges that can be assessed with the Ansys-exclusive SOFT analysis.

Why continue with the “build and break” mindset or struggle with homebrew code when technology can liberate your design, create a better product, and save you money? At Ansys, we are powering innovation that drives human advancement.

References

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AIAA 2024-1029.c1, Correction: Aero-Optical Simulation in Ansys FLUENT; Application and Validation, Mohammed S. Kamel, Zoran Dragojlovic, Valerio Viti, Felipe Mercado, Rongguang and Steven La Cava, Ansys

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