Analysis of thermally loaded transmissive optical elements

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ABSTRACT

The performance metrics of many optical systems are affected by temperature changes in the system through different physical phenomena. Temperature changes cause materials to expand and contract causing deformations of optical components. The resulting stress states in transmissive optics can cause refractive changes that can affect optical performance. In addition, the temperature changes themselves can cause changes in the refractive properties of transmissive optics. Complex distributions of refractive indices that relate to the thermal profile, the thermo-optic refractive index profile, within the optical media can be predicted by the finite element method. One current technique for representing such refractive index profiles is through the generation of optical path difference (OPD) maps by integration along integration paths. While computationally efficient, this method has limitations in its ability to represent the effect of the index changes for rays associated with multiple field points and multiple wavelengths. A more complete representation of the thermo-optic refractive index profile may be passed to the optical analysis software through the use of a user defined gradient index material. The interface consists of a dynamic link library (DLL) which supplies indices of refraction to a user defined gradient index lens as ray tracing calculations are being performed. The DLL obtains its refractive index description from a database derived from the thermal analysis of the optics. This process allows optical analysis software to perform accurate ray tracing for an arbitrary refractive index profile induced by changes in temperature.

Keywords: Integrated analysis, FEA, optomechanics, thermo-optic, dn/dT

1. INTRODUCTION

Figure 1 illustrates the flow of optomechanical analysis beginning with a thermal analysis and resulting optical performance predictions. The topic of this paper concerns the shaded path in which temperatures predicted by the thermal model are transformed into a refractive index change profile and passed to the optical analysis.

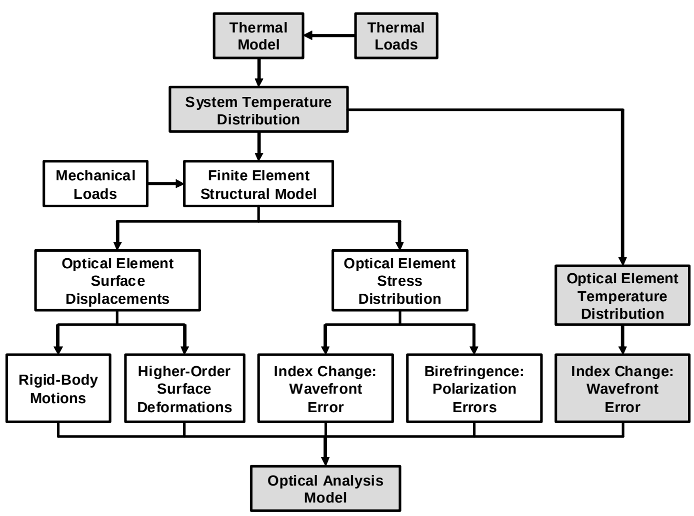

Figure 1: Flow chart of integrated optomechanical analysis.

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Figure 2 shows two methods of representing the refractive index change profile. One method is to perform an integration through the profile of each lens element to generate an OPD map to be applied to the entrance surface of each lens.[1,2] A second method is to use a DLL that interfaces to the optical analysis to provide the optical analysis with a user defined gradient index lens material. This user defined gradient index lens material is represented by a database containing a three dimensional refractive index change profile. As the optical analysis proceeds the DLL is queried for the refractive index and refractive index gradients at requested locations in a specific lens element. The DLL queries the database for the requested values and returns the data through a subroutine interface.

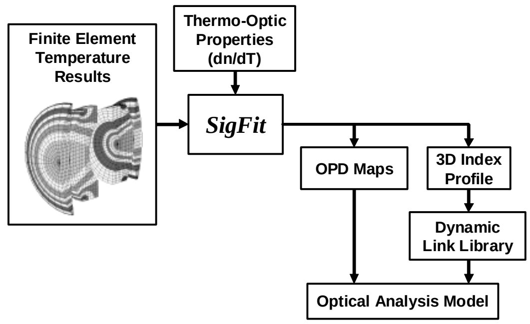


Figure 2: Flow chart of thermo-optic analysis.

The two representations discussed above are not equivalent. While the OPD map methods is computationally inexpensive it is limited in its ability to accurately represent the effects of the three dimensional refractive index change profile for multiple field points and wavelengths. The DLL method, while accurate for use with multiple field points and wavelengths, is significantly more computationally expensive than the OPD method.

2. INDEX CHANGES REPRESENTED BY OPD MAPS

2.1 Theory of OPD Map Representations

The calculation of OPD maps representing the effect of refractive index changes due to temperature changes is performed by integrations along paths as shown in Figure 3. Each finite element node on the entrance surface to the lens element is used as the origin of an integration path that extends through the lens. The orientation of the path is defined by the apertures on the entrance and exit surfaces of the lens element as shown in Figure 3.

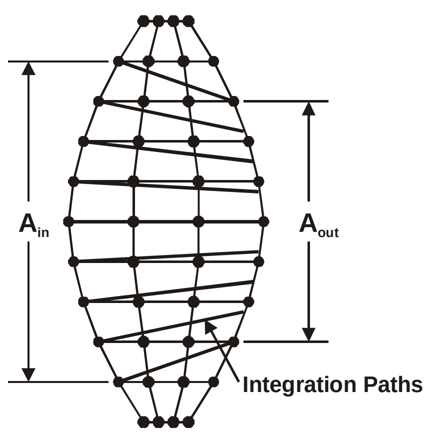


Figure 3: Integration paths through a finite element representation of a lens element defined by apertures.

The integration of OPD performed along each path is given by,

$$OPD = \sum_{i=1}^{NINT} \frac{dn}{dT}\left(T_i - T_{ref}\right)\Delta L_i \, , \qquad (1)$$

where $\frac{dn}{dT}$ is the thermo-optic coefficient, T_i is the temperature at the i^{th} integration point, T_{ref} is the reference temperature, and ΔL_i is the path length associated with the i^{th} integration point. The temperatures at integration points are found through interpolation from finite element temperature predictions. Figure 4 shows an illustration of an integration point within a finite element.

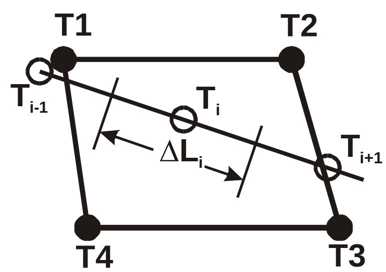


Figure 4: Illustration of an integration point within a finite element.

The figure shows a two-dimensional representation of what is actually a three dimensional computation but the concept is the same. The nodal temperatures, T1, T2, T3 and T4 are used in conjunction with the location of the integration point and the finite element shape functions of the element to compute an interpolated temperature, T_i, at the integration point. These interpolated temperatures are then used to conduct the integration shown in Equation 1 for all paths originating at the nodes on the entrance surface of the finite element representation of the lens. This process results in a map of OPD values over the entrance surface. This map may then be characterized by a polynomial fit or interpolated to a rectangular array for importation into the optical analysis. As the optical analysis traces rays through the optical system OPD values are accumulated to each ray as are found from the intersections with the OPD maps on each entrance surface.

2.2 Limitations of OPD Map Representations

In the generation of the OPD map representation of the thermo-optic effect integration paths must be chosen as described above. It is important to understand that a single integration path cannot capture the thermo-optic effect for all rays that pass through the initial starting point. This is because rays from different field points may pass through the same point on a surface but at different angles causing them to undergo a different subsequent path through the lens. This behavior is illustrated in Figure 5 in which an integration path is shown in comparison to two rays A and B. Ray A will experience a thermo-optic effect more similar to the integration path than the thermo-optic effect of Ray B. Optical systems exhibiting stronger variabilities in ray angles for rays intersecting the same point will be prone to greater inaccuracy when using the OPD map method to represent the thermo-optic effect.

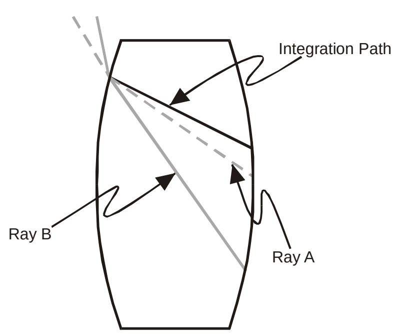


Figure 5: Ray traces relative to an integration path along which OPD is computed.

The OPD map method is also unable to represent the effect of the change in the thermo-optic coefficient with wavelength. There is no capability with the OPD map format to allow for the OPD map to be defined as a function of wavelength. Therefore, when the integrations that generate the OPD maps are performed the thermo-optic properties of the glasses must be evaluated at a single wavelength in order to generate a single OPD map per lens element. Use of this OPD at other wavelengths may give inaccurate results if the thermo-optic properties of the glasses are highly dependent on wavelength.

Both of the above limitations may be overcome if sets of OPD maps are generated for each field point and each wavelength and then used in the optical analysis accordingly. However, customized macros for optical analysis would be required to load the applicable OPD maps as each wavelength and field point combination was considered. These limitations are the motivations for development of a more complete representation of the thermo-optic effect for import into optical analysis.

3. INDEX CHANGES REPRESENTED BY A USER DEFINED GRADIENT INDEX MATERIAL

3.1 Implementation

Most popular commercial optical analysis products have a feature in which the user may specify the refractive properties of a glass through the use of an external subroutine called a user defined gradient index lens (UDG). The external subroutine is often a DLL which may be designed to function in accordance with the optical analysis software. The purpose of the DLL is to provide the optical analysis with the refractive properties of a glass at any point within the glass.

To begin a database file is generated containing the finite element model (FEM), temperature results from thermal analysis and the thermo-optic properties of all lens elements. This database is written in a format so that it may be read by the DLL software used during the optical analysis.

The interface to the optical analysis happens through a subroutine call to the DLL as ray tracing calculations proceed. The process is illustrated in Figure 6. The flow chart is an illustration of the evaluation of the refractive index at a single point of a single lens element and would happen many times as the ray tracing calculations are being performed.

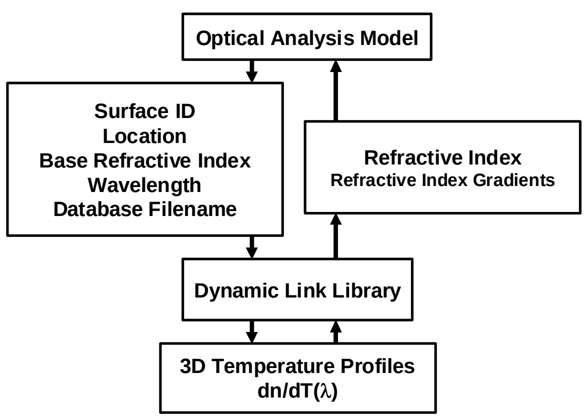
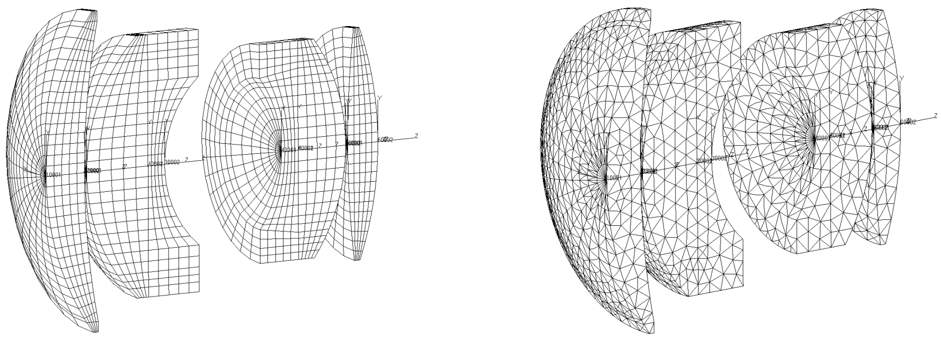


Figure 6: Flow chart of communication between optical analysis and the user defined gradient index dynamic link library.

The cycle of communication begins with a request by the optical analysis to the DLL for the index of refraction for a particular location of a particular lens element. Other information passed includes the refractive index without the thermo-optic effect (called the base refractive index), the wavelength currently being traced through the optical system, and the file name of the database containing the temperature and thermo-optic property information. The DLL then queries the database to obtain the refractive index that includes the effect of the change in temperature. The process of obtaining the refractive index uses the same shape function interpolation method used during integration in the OPD map method. The DLL also obtains the refractive index gradients required by the optical analysis. These computations are performed with the thermo-optic coefficient that is consistent with the wavelength specified by the optical analysis for the current request. Once refractive index data is computed the DLL returns the values to the optical analysis.

3.2 Examples

Implementation of thermo-optic analysis using the user defined gradient index capability has been developed in SigFit™.[3] The feature currently supports interfacing with the compatible feature in Code V™ and ZEMAX™.[4,5] An example was run with a double gauss lens assembly. Two FEMs of the double gauss lens assembly, shown in Figure 7, were constructed of different elements. While one model was meshed of 8-noded hexahedron elements, the other model was meshed of 10-noded tetrahedron elements. An important difference between these two models in their use with the user defined gradient index is that while the 8-noded hexahedron elements use tri-linear shape functions, the 10-noded tetrahedron elements use quadratic shape functions.



(a) (b)

Figure 7: Finite element models of a double gauss lens assembly meshed with (a) 8-noded hexahedron elements and (b) 10-noded tetrahedron elements.

A synthetically generated temperature profile was created for each example model using an axisymmetric distribution varying parabolically with respect to the radial coordinate. The generated temperature profiles, shown in Figure 8, allows representation of the index profile by the polynomial gradient index (PGI) lens features available in the optical analysis software as well as the OPD and user defined gradient index methods. This allows for a point of comparison in evaluating the OPD and user defined gradient index methods.

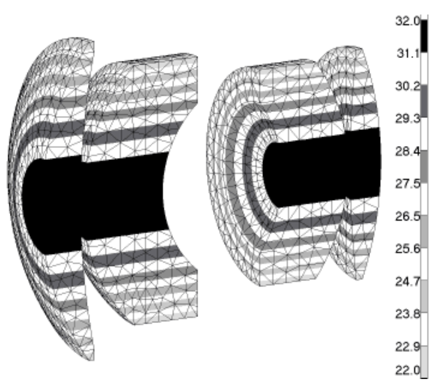
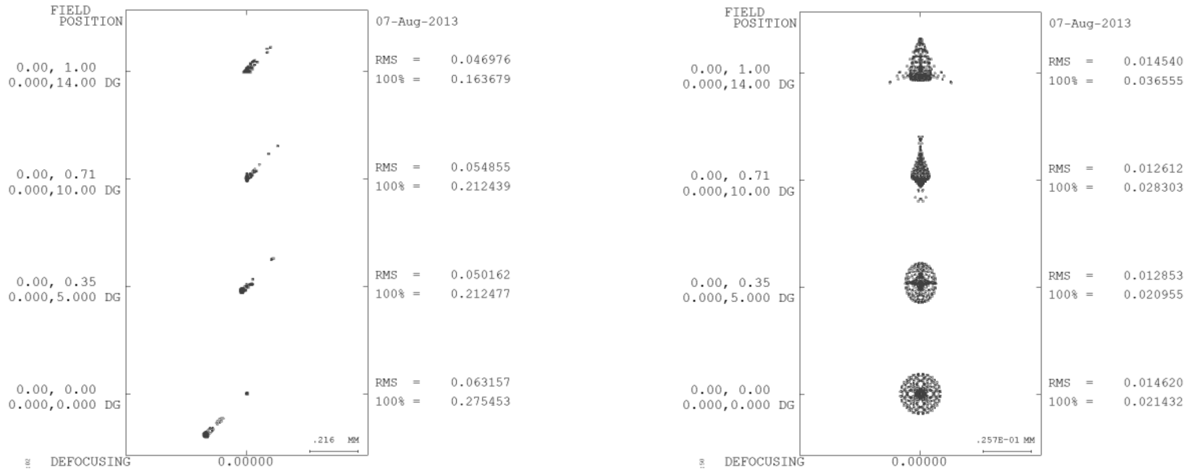


Figure 8: Synthetically generated temperature profiles parabolic with radius shown on the finite element model of the double gauss lens.

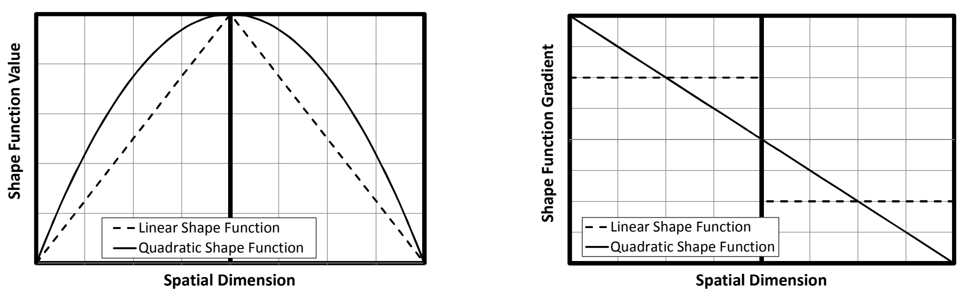
This temperature profile was imported into SigFit™ along with the FEM to generate a database to be used with the user defined gradient index lens feature of optical analyses software. After applying the thermo-optic predictions with the user defined gradient index capability in Code V™ was found that ray tracing with the data generated from the FEM meshed of 8-noded hexahedron elements was problematic. A comparison of the spot diagrams for analyses conducted with each element type is shown in Figure 9. The figure shows that using the tri-linear elements gives ray traces that wander randomly while using quadratic elements gives much more reliable ray tracing results.



(a) (b)

Figure 9: Spot diagrams of double gauss lens assembly with synthetically generated temperature profile for (a) 8-noded hexahedron elements and (b) 10-noded tetrahedron elements.

The reason for the difficulty is that the low order elements of the FEM meshed of 8-noded hexahedron elements fail to provide accurate gradient index information due to the order of the shape functions of the finite elements. Figure 10 shows an illustration of the interpolated temperatures and temperature gradients across two neighboring elements for which the temperature gradient at the interface between the elements is zero. The quadratic shape functions exhibit significantly more accurate and more continuous behavior for representing spatially varying index profiles.



(a) (b)

Figure 10: Illustration of (a) shape functions and (b) shape function gradients of neighboring elements for linear and quadratic elements.

SigFit and the finite element model were used to generate both the OPD and user defined gradient index characterizations corresponding to the generated temperature profile. Additionally polynomial characterizations of the thermally disturbed index profile were created. Wavefront analyses were performed for four different index states as shown in Table 1.

Table 1: States of Refractive Indices for Which Wavefront Analysis is Performed

State of Refractive Index	Code	Description of Characterization of Refractive Index Profile
Nominal	NOM	Nominal refractive indices are assigned to each glass.
Polynomial Gradient Index	PGI	Refractive indices are assigned polynomial shapes corresponding to the temperature profile and the thermo-optic coefficient of each glass.
Optical Path Difference	OPD	Optical path differences are calculated by integration using Eqn. (1) and formatted into Zernike polynomial fits for each lens element's entrance surface.
User Defined Gradient Index	UDG	Temperatures and thermo-optic coefficients are stored in a database to be used by the user defined gradient index capability.

Comparison of the OPD and UDG results was performed by computing the root-mean-square (RMS) of the difference in wavefront from PGI and normalizing by the root-mean-square (RMS) of the difference in wavefront from NOM to PGI. That is,

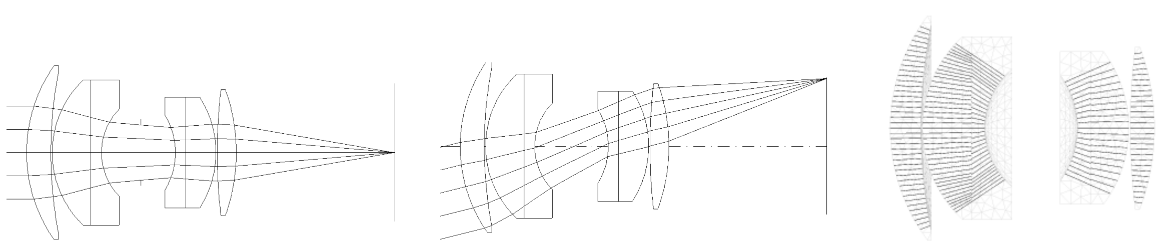
$$\%Error\ OPD = \frac{\mathrm{RMS}(OPD - PGI)}{\mathrm{RMS}(PGI - NOM)} \qquad \%Error\ UDG = \frac{\mathrm{RMS}(UDG - PGI)}{\mathrm{RMS}(PGI - NOM)} \tag{2}$$

The differences between wavefronts were computed by term by term subtraction of the Zernike polynomial fits to each wavefront map at the pupil. Table 2 shows the results of the percent error calculations.

Table 2: Errors in Wavefront Predictions vs. Field Point for OPD and UDG Methods

Field Angle (Degrees)	% Error in OPD Method	% Error in UDG Method
0	5.0%	0.0%
5	6.5%	0.0%
10	13.5%	0.1%
14	26.4%	0.1%

The error in the prediction using the OPD method can be seen to arise from the greater inconsistency between the paths of the rays for the off-axis field points and the integration paths used to conduct the OPD integration.



(a) Ray trace of on-axis field point (b) Ray trace of off-axis field point (c) OPD integration paths

Figure 11: Illustrations of real ray traces and OPD integration paths.

While the accuracy of the UDG is superior to the accuracy of the OPD method, the computational efficiency of the OPD method is orders of magnitude more superior to the UDG method. This difference in computational efficiency motivates improving of the accuracy of the OPD method. Improvement of the accuracy of the OPD method is being developed by testing the use of intermediate wavefront maps at several surfaces within each surface. Such intermediate wavefront maps are being generated by section-by-section integration between parametric surfaces within each lens. This approach will require each lens to be modeled as several lenses unless capabilities within the optical analysis software can be developed to define wavefront maps located at intermediate surfaces within a lens element. A second approach being considered is to perform OPD integration for each field point using ray trace data from the optical analysis software. Improvements are also being considered to improve the efficiency of the UDG method by characterizing the temperature profiles with three-dimensional polynomials, which can be evaluated more efficiently than finite element interpolation.

4. SUMMARY

While the OPD integration method for thermo-optic analysis offers some utility at minimum computational expense, a more accurate method must be employed for some optical systems. The UDG method offers excellent accuracy but at significant computational expense including the requirement to use quadratic elements in the finite element heat transfer analysis. Future development work will seek to employ methods achieving both accuracy for wide-field systems and computational efficiency.

REFERENCES

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[3] SigFit is a trademark of Sigmadyne, Inc.
[4] Code V is a registered trademark of Synopsys, Inc.
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