Challenges in Integrated Optomechanical Analysis

Victor Genberg and Gregory Michels
Sigmadyne Inc., 803 West Ave, Rochester, NY 14611
genberg@sigmadyne,com

Abstract: Computational analysis is commonly accepted in both optical and mechanical design. Integrating the two diverse fields to predict optical performance under mechanical environments presents several challenges which will be addressed in this paper.

Introduction:

When mechanical engineers undertake their first analysis of an optical structure, they must be aware of the differences from traditional mechanical structures. Most traditional structures are made of ductile materials such as steel or aluminum. The analysis is based on comparing Von Mises stress to material yield. Lenses and mirrors are often composed brittle glass or ceramics, in which the failure is fracture based on maximum principal stress. If ductile materials are used in an optical system, failure may be based on the precision elastic limit (micro-yield) rather than the common 0.2% offset yield.

Another difference is that optical structures are designed to be stiffness limited, rather than stress limited as in conventional design. If an optical structure deflects too much, it will fail to produce acceptable performance. In operation, an optical system with satisfactory performance is usually under low stress.

Size matters. In traditional structures, deflections and tolerances are measured in millimeters. In optical structures, deflections and tolerances are measured in microns or nanometers.

Thus, the mechanical engineer must adjust to the differences required for optomechanical analysis. The engineer faces two other obstacles, optical terminology and optical software. This paper will address the issues and challenges with integrated optomechanical analysis.

The authors have extensive experience in this topic[1] as part of the development of the commercial code SigFit[2]. Examples from SigFit will be used throughout this paper.

Challenge: getting displacements from FE codes:

A finite element (FE) analysis will include displacements of every node in the model, including the metering structure, bonds, and other support structures. The optical analysis only requires displacements of the optical surface, which must be processed before passing to optical codes. The effort required to obtain the FE model and displacements vary significantly for FE software. For example. Nastran provides model and results in readily available ASCII format[3]. Other programs require special code using their API interface[4].

To understand and process the FE results, the user must specify which nodes belong to which surface. In SigFit, the user specifies a named entity or numbered property in the FE model for each optical surface. The procedure varies from FE code to FE code. The user must also specify which load cases should be sent to the optics code. Again, this is easier in some FE codes than others.

Once the proper FE data has been collected, it must be processed. Displacements must be converted to local coordinate system of each surface aligned with the optical model. At this point, radial correction must be applied to account for the impact of radial growth on the sag displacement[1]. In the Figure 1 below, an optical surface has growth due to isothermal temperature change. It can be seen that the sag displacement is NOT the same as Z displacement in the presence of radial growth. In the figure, the Z displacement is positive, but the sag of the surface is negative.

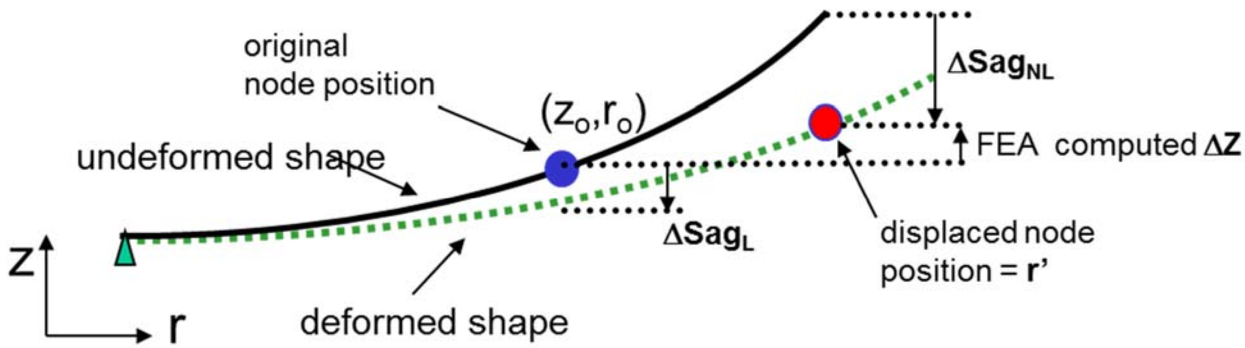


Figure 1: Isothermal growth of an optical surface

Challenge: passing displacements into Optics codes:

Optics codes are not written to accept FE results. To get the environmental effects into the optical analysis, the data must be processed and converted to a form allowed by each optics code.

When passing results to an optics code, the data must agree with the optics model for

1) Model units
2) Surface numbering and type
3) Coordinate system orientation
4) Data formats

To facilitate the coordination, the user may view the optics model in SigFit and select the desired surface data directly. This reduces the chance for transcription errors.

Optics codes treat rigid-body motion more accurately and efficiently than polynomial data. In a ray trace, the intersection with the rigid-body motion is a closed form calculation, rather than the iterative technique required with polynomial input. Confusing issues with rigid-body motion include:

1) Rotation signs: CodeV use left-handed Rx and Ry, but right handed Rz
2) Units: CodeV and Zemax use degrees for rotations, not radians.
3) Zemax has no Z rigid-body, it is treated with a THICK command.

Elastic distortions of a surface may be represented as best-fit polynomials or as grid array data which will be addressed in the next sections.

Challenge: representing surface displacements as polynomials:

A subject as simple as Zernike polynomials can be very confusing to the novice because of the following:

1) Combining distortion polynomials with prescription polynomials
2) Amplitude normalization
3) Radial normalization
4) Numbering/order
5) Missing terms
6) Sag vs normal displacement

Each topic is discussed below.

1) If a surface is defined as a conic in the nominal prescription, the distortion best-fit polynomials must be added to the prescription, changing the surface type to Zernike for instance. If the prescription is asphere, then the aspheric and Zernike terms must be combined and redefined as a Zernike surface. When combining polynomials, care must be given to use a consistent radial normalization.
2) Born and Wolf define Zernike polynomials as having unit amplitude at the normalizing radius. Noll defines Zernike polynomials so that they have unit RMS over the normalizing circle (Table 1)
   a. CodeV uses unit amplitude normalization for standard and Fringe Zernikes
   b. Zemax uses unit RMS normalization for standard Zernikes
   c. Zemax uses unit amplitude normalization for Fringe Zernikes.

	Normalization	
Zernike Term	Unit Amplitude	Unit RMS
Focus (n = 2)	$2r^2 - 1$	$\sqrt{3}\left(2r^2 - 1\right)$
Spherical (n = 4)	$6r^4 - 6r^2 + 1$	$\sqrt{5}\left(6r^4 - 6r^2 + 1\right)$

Table 1: Zernike polynomial normalization

3) Radial normalization is the radius value at which the Born and Wolf Zernikes have a unit amplitude, or Noll polynomials have unit RMS. Polynomials must be converted to a common radial normalization before combination.
4) The numbering (ordering) of Zernike polynomials vary from code to code. For example, consider the astigmatism terms in table 2. More extensive tables of numbering are given in Ref 1.

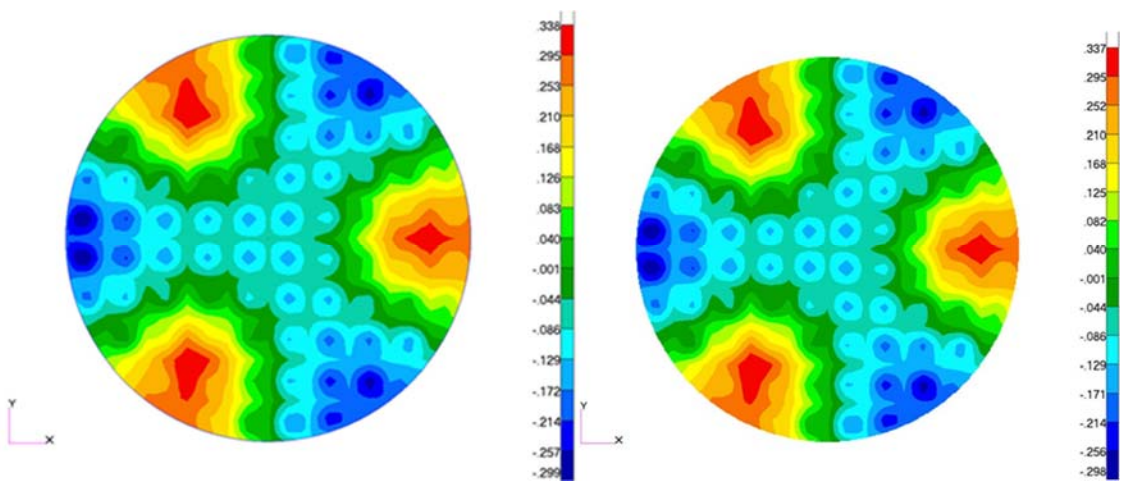
Zernike Term	Standard Zernike Order CodeV	Standard Zernike Order Zemax	Fringe Zernike Order
$r^2\cos(2\theta)$	Z04	Z06	Z05
$r^2\sin(2\theta)$	Z06	Z05	Z06

Table 2: Zernike polynomial ordering

5) Some optics code polynomial representations (asphere for example) do not include a constant term which is required for proper best-fit polynomial fitting. The constant term must be added to the rigid-body Z displacement (or thickness term).
6) In Zemax, polynomials must be fit to the sag displacement. In CodeV, the polynomials may be fit to the sag or the normal displacement. If fit to sag, displacement, SigFit uses the polynomials to redefine the surface as in item 1 above. If fit to normal displacement, SigFit will write the polynomials to CodeV as an interferogram file, which was originally created to represent test data.

Challenge: representing surface displacements as grid array:

There are times when the chosen polynomials do not provide a good fit to the distortions. The user may select may select different polynomial types, but the choice in optics codes is limited to aspheres, Zernikes and XY polynomials. The user may request higher order terms, but each optic code has a limit on the number of terms. For the example of quilting in a lightweight mirror (Figure 2), higher order terms do not represent the deformation. An interpolated array can represent quilting accurately.



FE Displacement plot — interpolated array 401x401

Figure 2: Interpolation on a light weight mirror with quilting

In SigFit, interpolation is based on the FE element shape functions with an option to use closest node technique. The element shape functions use a consistent theory with the FE model and are more accurate than closest node methods. If the FE model has valid slope data (i.e. shell elements), then SigFit will use the shell bending equations for interpolation for even higher accuracy as shown in Figure 3.

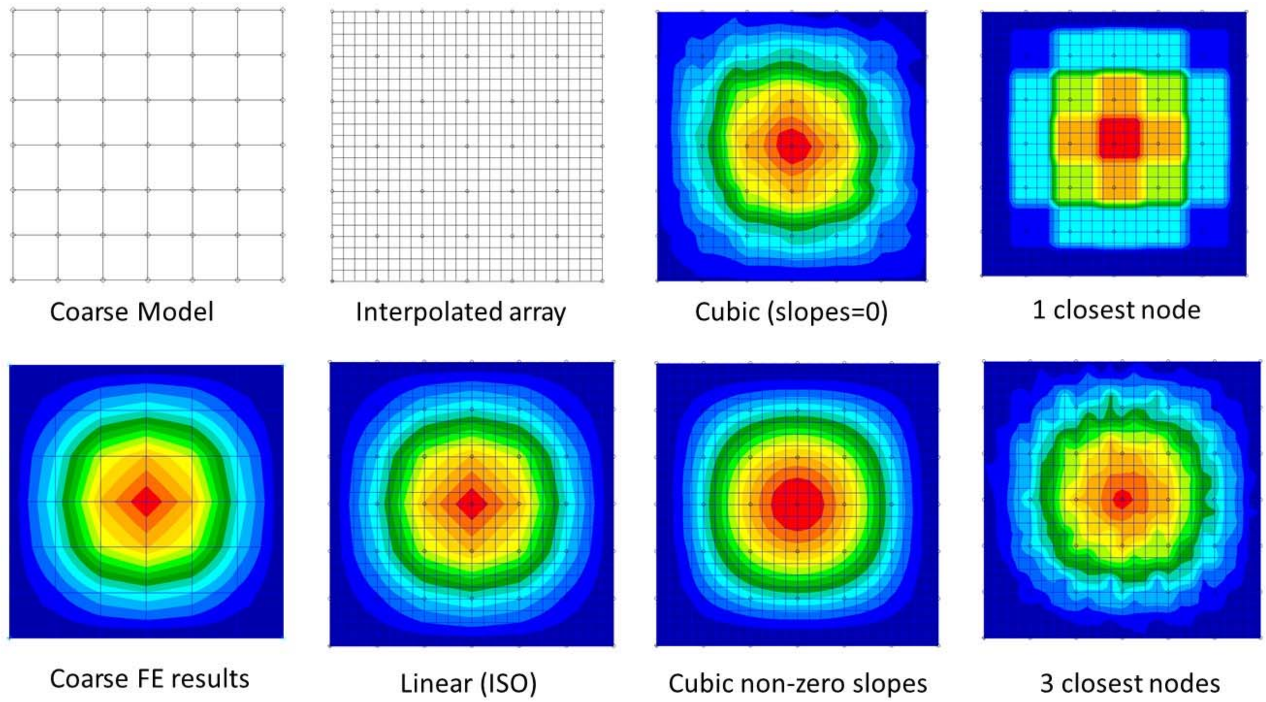


Figure 3: Comparison of interpolation techniques

If only sag displacements are interpolated, Zemax will use multiple points to fit bi-cubic polynomials to the data. If slope data is interpolated, Zemax can be more accurate locally with their bi-cubic polynomials.

Reading and writing CodeV grid interferogram files is a challenge for the uninitiated. The real data must be converted to integer data by a scaling value. Grid points outside of the optic are represented by a no-data value of 32767. See Figure 4 for an example.

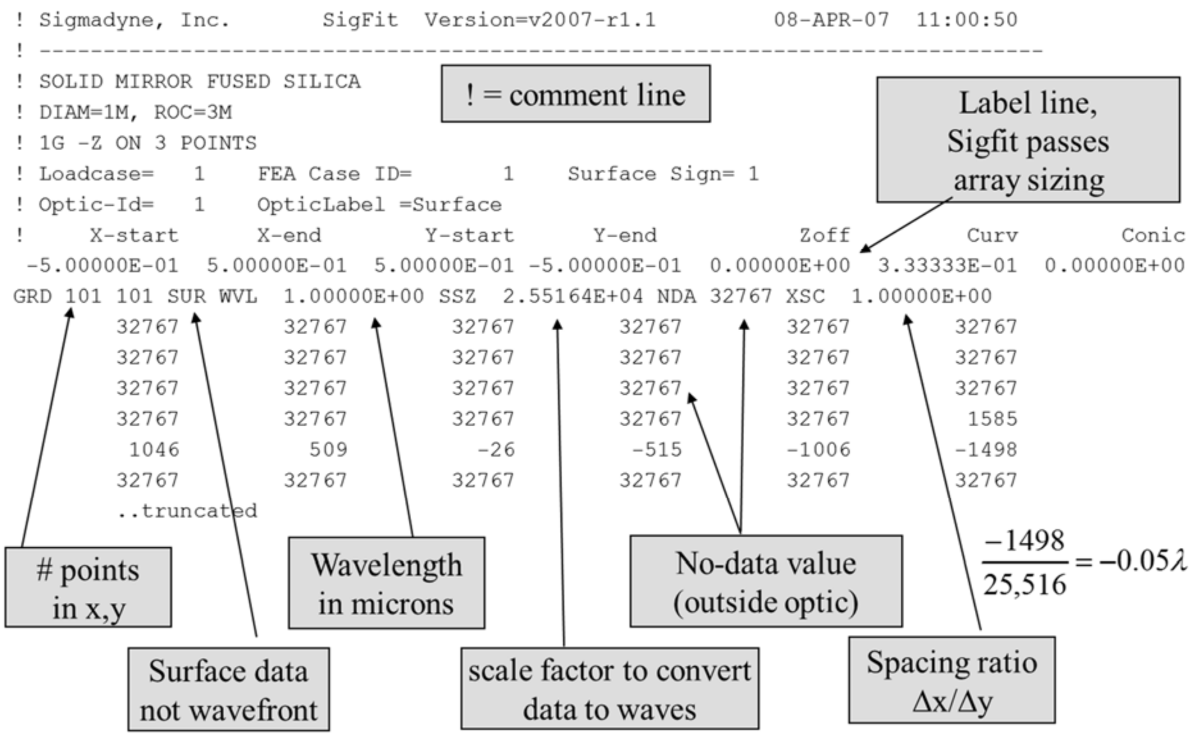


Figure 4: interferogram grid array file

Challenge: Calculating the effect of vibrations on optical performance

In transient response analysis, results at any time step can be treated the same as static analysis results. The user only need to choose which snapshots in time to pass to the optics codes. To capture meaningful results, a very large number of snapshots are required

In steady-state harmonic response analysis, damping causes the results to be complex numbers representing magnitude and phase. Optics codes do not accept complex deformations. At any given forcing frequency, the surfaces are oscillating sinusoidally. One option is to step though the complete cycle from zero to 2π at any given forcing frequency, and output several deformed shapes for the optics code. For multiple frequencies this can be a massive amount of data. See Figure 5 for a single forcing frequency.

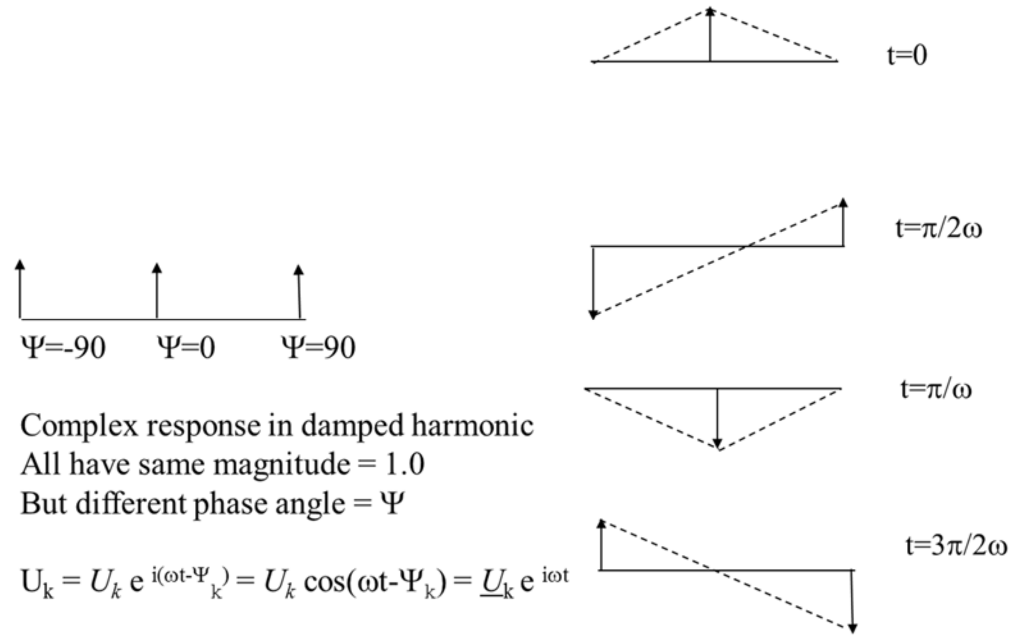


Figure 5: Harmonic response with equal magnitudes but different phases

SigFit has a dynamic analysis capability to simplify harmonic analysis. Most FE harmonic response analyses use modal analysis methods as does SigFit. The key to getting meaningful optical results is to decompose mode shapes into rigid-body motion and elastic distortion before harmonic analysis. This allows the results of the harmonic analysis to be accurately represented as rigid-body pointing error and residual surface error.

In random response analysis, the input, and therefore the output, is represented statistically. Only magnitude is output. All phasing of results is lost. Thus in Figure 6, the 3 nodes have the same magnitude, but the phasing in (a) is all bias, whereas the phasing in (b) is all elastic distortion. These have widely different impact on optical performance. SigFit addresses this issue by decomposing the mode shape data before the random response analysis. SigFit will represent the response as rigid-body and residual surface error. In addition, SigFit will list each modes contribution to each result which becomes a great design diagnostic tool.

Figure 6: Random response with equal magnitude and different phase

Challenge: calculating Line-of-Sight:

Optics codes can create line-of-sight (LOS) coefficients. The challenge for the mechanical engineer is to convert the optics output to fit a FE model. Conversion includes:

1) Convert left-hand rotations to right-hand
2) Convert degrees to radians
3) Convert units
4) Align coordinate systems
5) Using FE node numbers
6) Add interpolation element to calculate average surface motion

Without proper communication, there are several opportunities for error. SigFit has a ray trace capability which allows it to automatically create LOS equations[5] for the FE model eliminating most sources of error (Figure 7). If the dynamic analysis is conducted in SigFit, each modes contribution to LOS will be listed, pointing to key modes to fix any problems. Another option is to output the effect on system MTF in harmonic or random response[6].

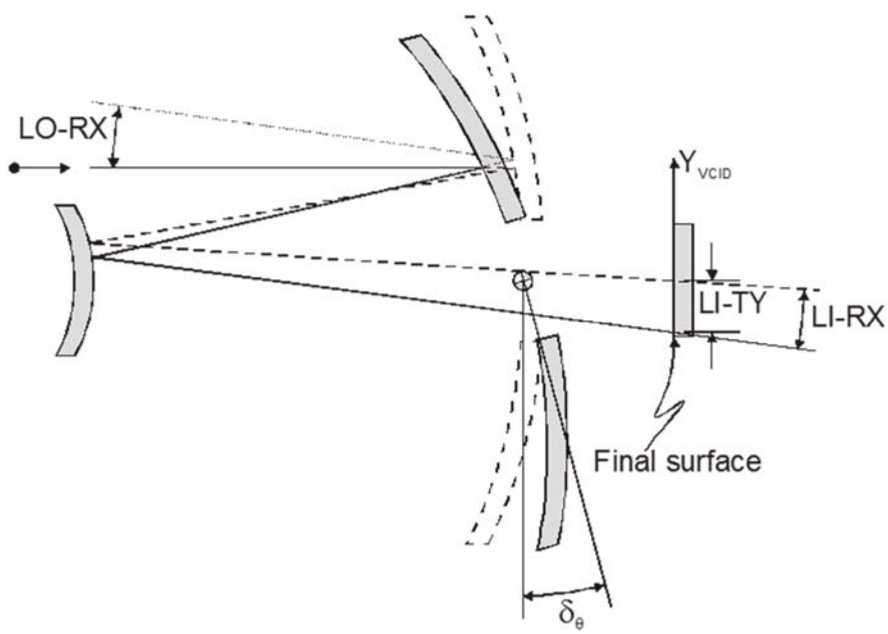


Figure 7: Line-of-Sight calculation

Mode	Freq	LI-TX	LI-TY	LI-TV
4	70.1	0.0	0.0	0.0
5	**73.8**	**9.9**	**49.1**	**16.8**
6	**73.8**	**11.3**	**49.1**	**18.0**
7	79.3	0.0	0.9	0.2
8	**79.3**	**44.0**	**0.9**	**36.4**
9	82.1	0.0	0.0	0.0
10	82.9	0.0	0.0	0.0
11	85.3	0.0	0.0	0.0
12	85.3	0.0	0.0	0.0
13	90.3	0.0	0.0	0.0

Figure 8: Each modes % contribution to LOS

Challenge: calculating Thermo-Optic effects in diffractive optics

The index change due to temperature can be a very important effect in optical performance. Optics codes can only represent radial gradients in polynomial form, not general FE thermal results. SigFit has two approaches[7] to this problem. The first approach is to integrate the index change due to temperature through the lens[8] and represent that effect is an OPD map on the lens entrance surface as shown in Figure 9. If the integration paths do not match the ray paths, the lens can be automatically broken into several layers for more accuracy.

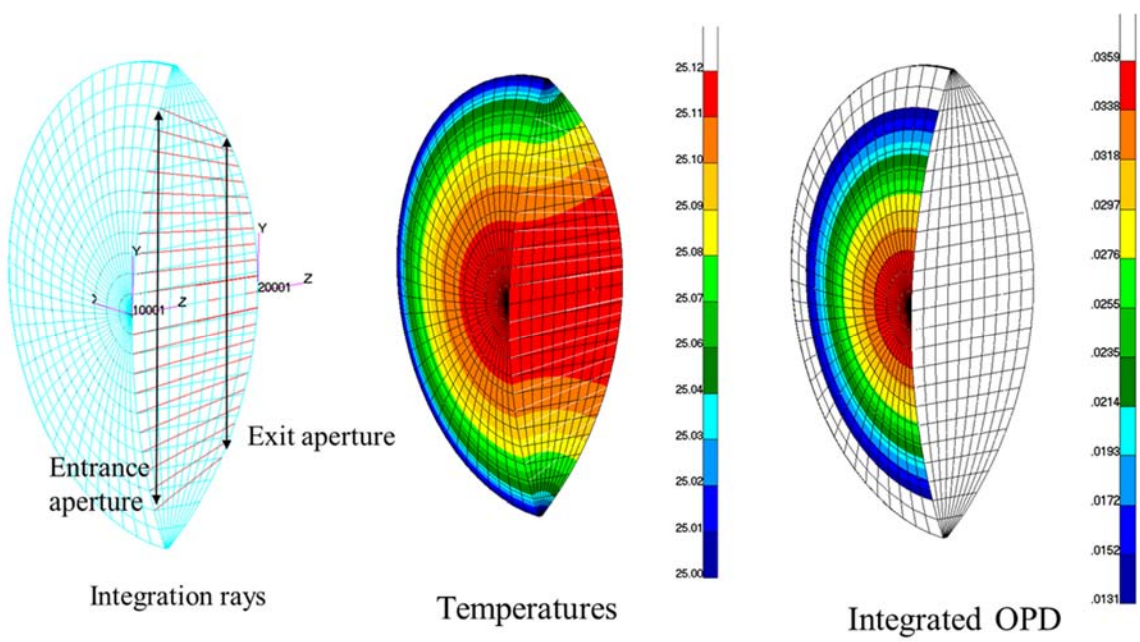


Figure 9: Thermo-optic analysis

The second approach is to use the CodeV gradient index lens capability. SigFit writes a database for the temperature results which the CodeV calls at each ray path point. SigFit returns the current index at that point. The higher accuracy comes at cost of slower analysis times.

Challenge: calculating Stress-Optic effects on optical performance

The effect of stress on index is usually less important than temperature. SigFit uses the same approach for stress effects[9] as temperature effects. The index effect is integrated through the lens and represented as an OPD map on the entrance surface. Figure 10 shows birefringence[10] results for test data, closed form analytical solution and a Nastran/SigFit analysis on a thin disk with three point radial load. In this simple example, the state stress had a closed form solution. The FE approach is more general and could be used on any geometry. The gradient index approach is not supported for stress, because the ray direction is required in addition to the ray point location. CodeV does not provide ray direction in its gradient index call.

SigFit will calculate stress birefringence effects and write BIRE and CAO files for CodeV. Zemax does not have a similar birefringence input capability.

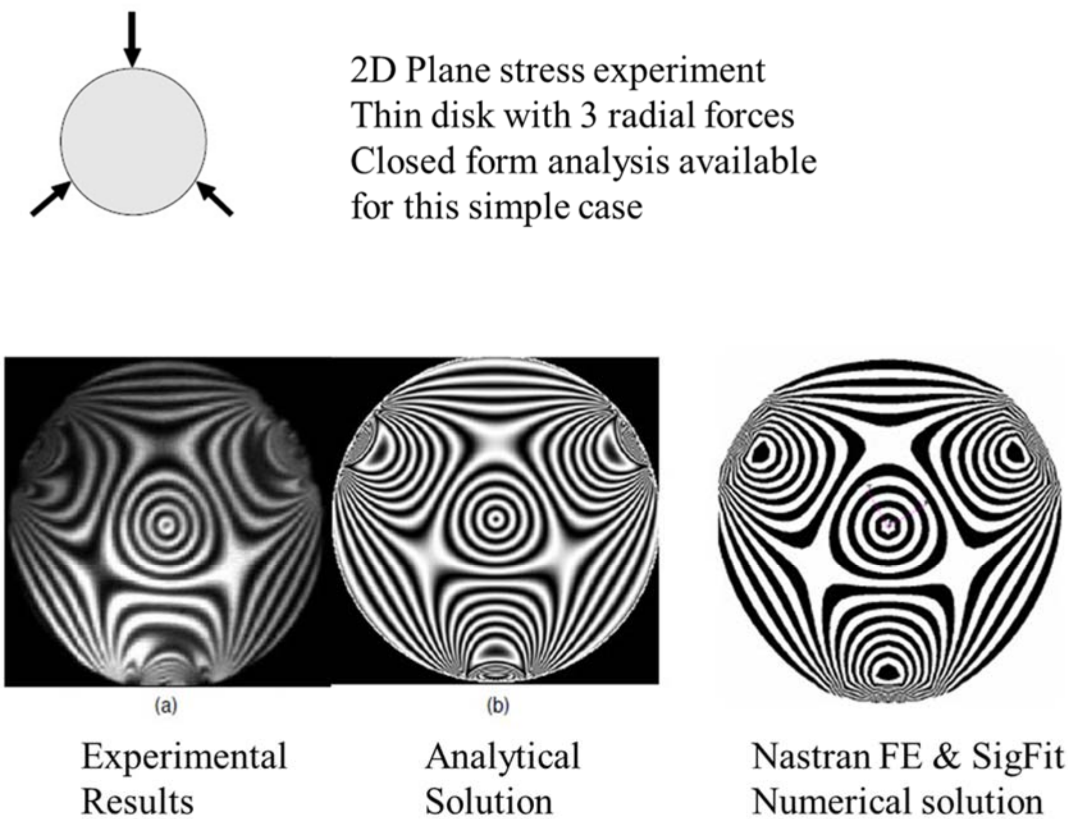


Figure 10: Comparison of birefringence from test and analysis

Challenge: Using optical performance metrics in mechanical design

In an optical system, the optical performance is the key design criteria. The mechanical design should use optical metrics in the design process. For example, when specifying interface tolerances on a mirror mount, mirror surface error should be a driving criterion. In the model below (Figure 11), determining mount flatness requirements was based on surface error.

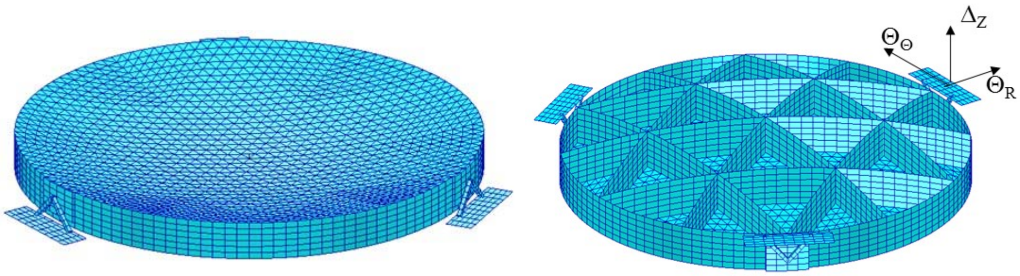


Figure 11. Mount flatness and coplanarity

Three unit load cases were applied to each of the 3 mounts. SigFit then used Monte Carlo techniques[11] to perform 1000 simulations where variables were randomly selected within a specified tolerance on each variable and the surface RMS error was calculated. The absolute maximum error, as well as the 90% confidence level error, were reported (Ref xx). The design engineer could then change tolerance levels to trade off resulting surface error verses the flatness requirement (and therefore cost) to reach a final design specification.

In the telescope model shown in Figure 12, the adaptive primary mirror was structurally optimized to satisfy system level wavefront error (WFE) under thermal and gravity loads[12,13]. The design variables were core and face thickness of the mirror as shown in Figure 12. Design constraints were placed on mirror stress, natural frequency, and system level WFE. The WFE was calculated from a linear optics model. The optimization was conducted in MSC/Nastran's solution 200 which called SigFit as a DRESP3 subroutine to calculate the adaptive mirror correction and the system WFE. The resulting design met all performance requirements while cutting the mirror weight in half (Figure 13).

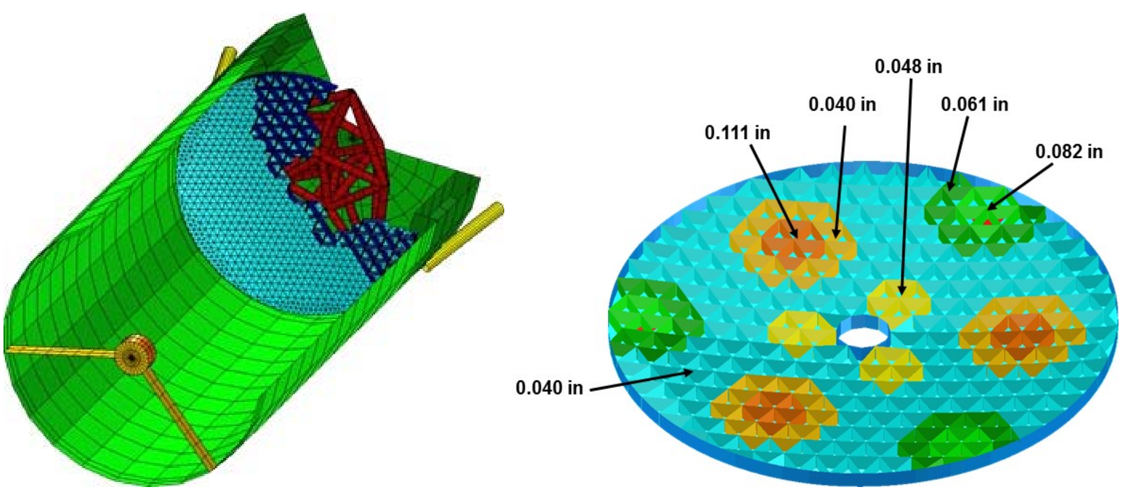


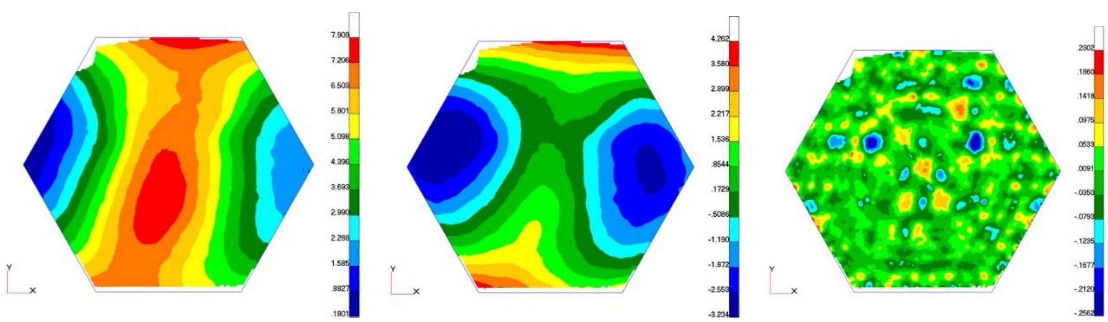
Figure 12: Telescope and optimized adaptive primary mirror

Response	Initial Design	Optimized Design	Requirement
Thermally Induced Wavefront Error	9 nm	20 nm	20 nm
Gravity Release Induced Wavefront Error	54 nm	60 nm	60 nm
Peak Launch Stresses	1000 psi	1000 psi	1000 psi
First Natural Frequency	231 Hz	221 Hz	200 Hz
Weight	20.8 kg	9.9 kg	Minimum
Areal Density	53.0 kg/m^2	25.2 kg/m^2	Minimum

Figure 13: Optimization results

Challenge: Combine optical test results with FE analysis

Interferogram arrays from optical test include the effects gravity, temperature, and test fixture as well as the residual polishing error. The interferogram array in Figure 14a represents raw test data interpolated on to the FE mirror model in SigFit. The FE predicted gravity distortions were subtracted along with best-fit plane and focus in Figure 14b. In Figure 14c, the actuators corrected the residual polishing error.



(a) (b) (c)

Figure 14: Test interferogram on an adaptive mirror

Summary

Many challenges to integrated optomechanical analysis have been discussed. A major challenge is getting the optical and mechanical analyses to talk to each other in a common language. This requires correlating units, sign conventions, ordering of data, and formats. These challenges are not advanced technology, but rather a bunch of very time consuming bookkeeping issues which are subject to error. An error in any one issue can invalidate the whole analysis.

Other challenges involve incorporating optical performance metrics into the mechanical design and analysis process. Optical surface error should be used in design optimization and tolerancing. Line-of-sight equations are necessary to understand jitter effects in vibration analysis.

With the proper tools, these challenges can be overcome.

References

[1] Doyle, K., Genberg, V., Michels, G., Integrated optomechanical analysis 2nd Ed, SPIE Press (2012)

[2] Michels, G., SigFit Reference Manual, Sigmadyne, Inc., Rochester, NY, 2011. (2012)

[3] Genberg, V., Michels, G., “Integrating MD Nastran with optical performance analysis”, MSC User Conference, (2011)

[4] Michels, G., Genberg, V., Doyle, K., “Integrating Ansys mechanical analysis with optical performance analysis using Sigfit”, Ansys users conference (2008)

[5] Genberg, V., Doyle, K., Michels, G., “Optical performance as a function of dynamic mechanical loads”, SPIE Paper 5178-4 (2011)

[6] Genberg, V., Michels, G., Doyle, K., “Integrated modeling of jitter MTF due to random loads”, SPIE Paper 8127-16 (2011)

[7] Michels, G., Genberg, V., “analysis of thermally loaded transmissive optical elements”, SPIE paper 8127-19 (2011)

[8] Genberg, V. L., Shape function interpolation of 2D and 3D finite element results, in *Proc. 1993 MSC World User's Conference*, Los Angeles, 1993.

[9] Doyle, K., Genberg, V., Michels, G., “Numerical methiods to compute optical errors due to stress birefringence”, SPIE Paper 4769-05 (2002)

[10] Beckley, A., Polarimetry and beam apodization using stress-engineered optical elements, PhD Thesis, Univ Rochester (2012)

[11] Genberg, V., Michels, G., Bisson, G., “Optomechanical tolerancing with Monte Carlo Techniques”, SPIE Paper 8125-10(2011)

[12] Michels, G., Genberg, V., Doyle, K., Bisson, G.,” Design optimization of system level adaptive optical performance”, SPIE Paper 5867-25 (2005)

[13] Michels, G., Genberg, V., ‘Using the DRESP3 to improve multidisciplinary optimization’, MSC/Nastran User Conf – Paper 43 (2011)