Opto-Mechanical I/F for ANSYS

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Abstract

Thermal and structural output from ANSYS is not in a form useful for optical analysis software. Temperatures, displacements and stresses at arbitrarily located FE nodes can not be input directly into optical software. This paper discusses the post-processing steps required to present ANSYS results in a useable format for CODEV, ZEMAX, and OSLO. Specific issues include optical surface deformations, thermo-optic effects, adaptive optics, and dynamic response. Finite element computed optical surface deformations are fit to several polynomial types including Zernikes, aspheric, and XY polynomials. Higher frequency deformations are interpolated to a user-defined uniform grid array using element shape functions to create interferogram files. Three-dimensional shape function interpolation is used to create OPD maps due to thermo-optic effects (dn/dT), which are subsequently fit to polynomials and/or interferogram files. Similar techniques are also used for stress birefringence effects. Adaptive optics uses influence functions to minimize surface error before or after pointing and focus correction.

Introduction

High performance optical systems require integrated optomechanical analysis to predict performance (Reference 1). This requires that finite element analysis (FEA) results be accurately passed to optical analysis programs (see Figure 1). Optical analysis programs have very limited input formats. Rigid body motions of optics are input using one file format, whereas elastic distortions are typically described as Zernike polynomials or rectangular arrays in a separate file.

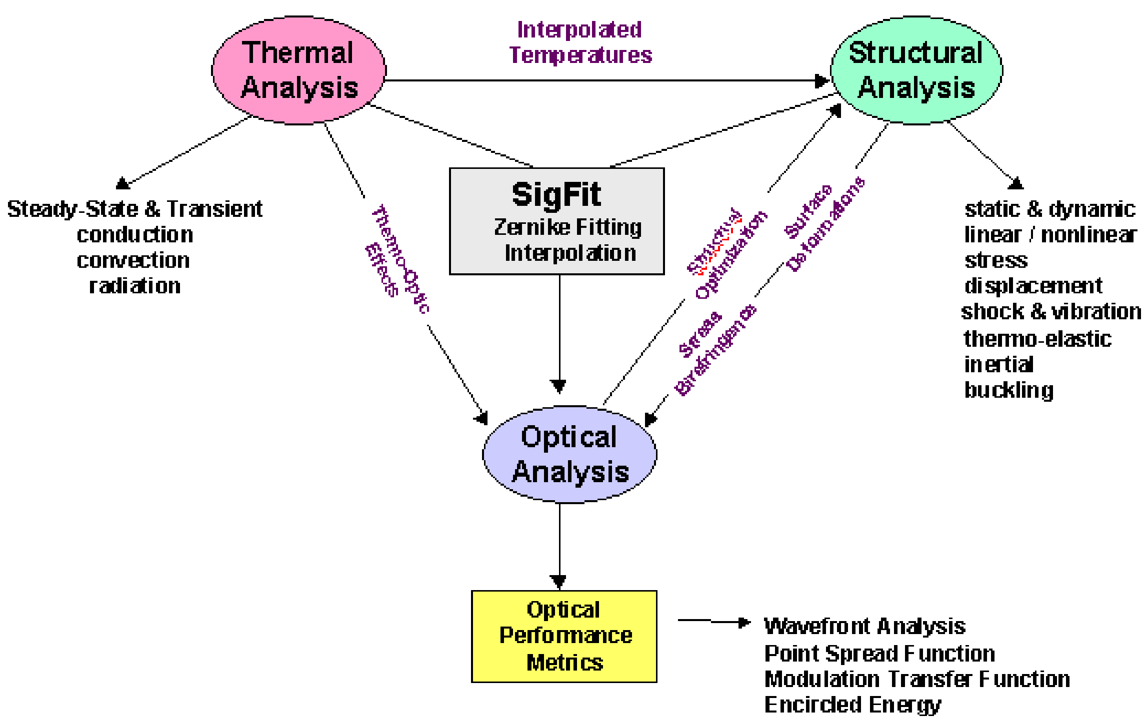
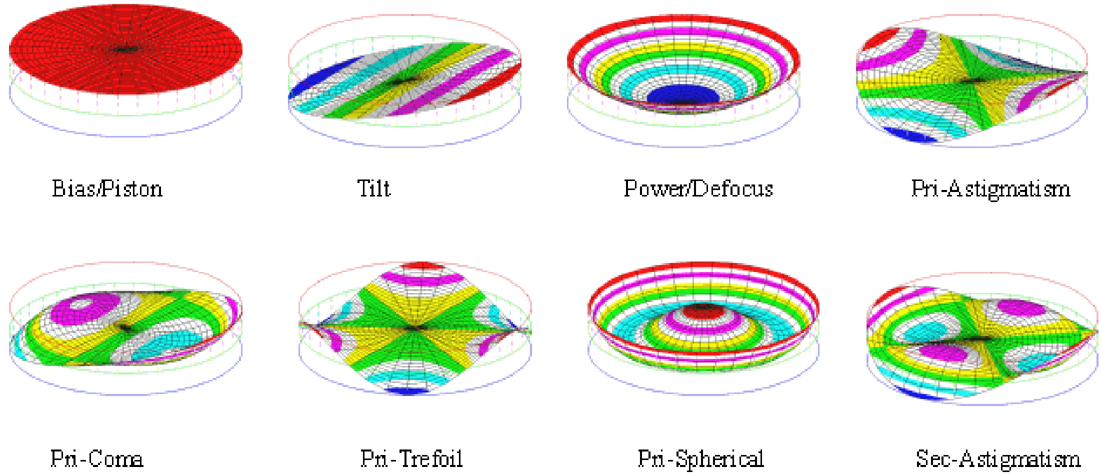


Figure 1. Integrated Analysis

Zernike polynomials are an infinite set of polynomials (see Figure 2) of radius raised to a power (N) multiplying sines and cosines of multiples (M) of polar angle. The terms N and M are referred to as the radial and circumferential wave numbers. These polynomials are similar to the Seidel aberrations used to represent optical performance (Reference 2).



$$\Delta Z(\rho,\Theta) = A_{00} + \sum_{N=2}^{\infty} A_{N0} R_0^N(\rho) + \sum_{N=1}^{\infty}\sum_{M=1}^{\infty} R_M^N \left[A_{NM}\cos(M\Theta) + B_{NM}\sin(M\Theta)\right]$$

Figure 2. Zernike Polynomials

Typical modifications to FEA data include:

- Convert units
- Align coordinate systems
- Switch rotations to left-handed system
- Fit displacements with Zernike polynomials
- Interpolate results from FEA mesh to a rectangular array

In a lens system, not only are surface distortions important, but also index of refraction changes due to temperature (thermo-optic effects) and stress (stress-optic effects) are required for a complete performance prediction. The index of refraction changes with temperature and stress and can significantly affect optical performance. To get these effects into the optical analysis, it is necessary to integrate through each optic and write the net effect as an optical path difference (OPD) file.

In this paper, an interface program called SigFit will be discussed which converts FEA thermal and structural results from ANSYS to optical analysis programs CODE V, ZEMAX, and OSLO. A typical analysis flow is shown in (see Figure 3).

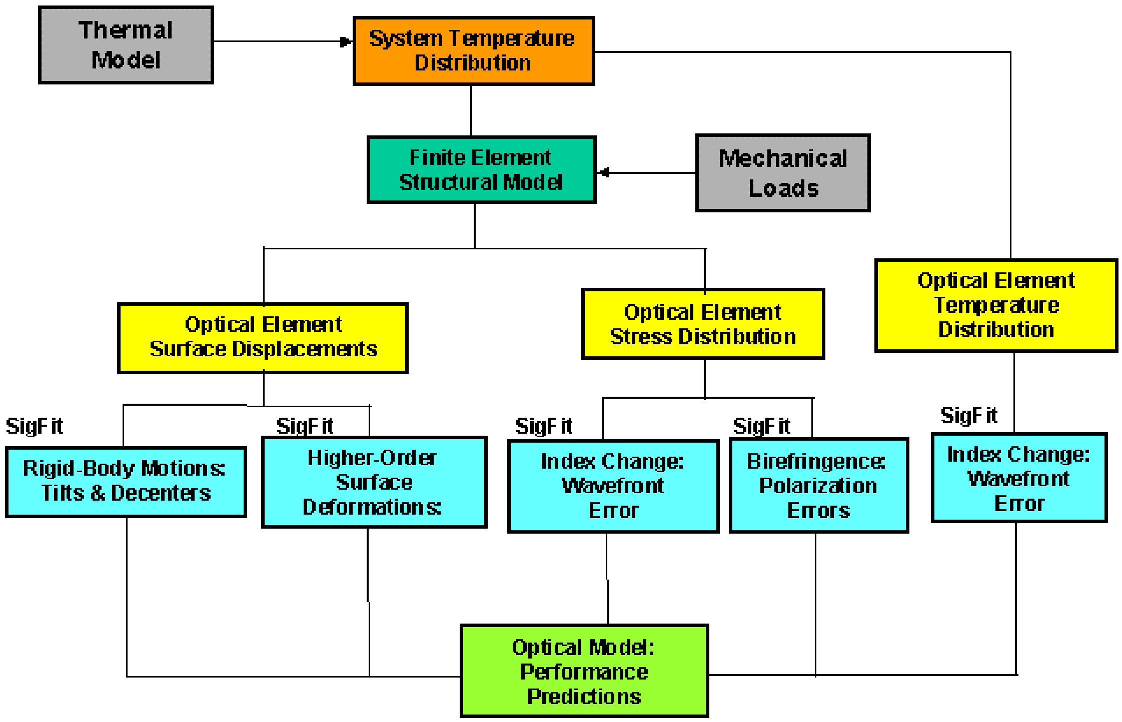


Figure 3. Analysis Flow

Structural Distortion

Often raw FEA results are dominated by rigid-body motion (see Figure 4) as in the deformed side view (see Figure 5). If the deformations are processed in SigFit, the rigid-body motions can be subtracted to see the elastic distortions, the elastic distortions with power removed, and the surface with all selected Zernike polynomials removed (see Figure 6). Subtraction of rigid-body motion allows the user to understand and quantify the elastic deformations by themselves and may also simulate rigid body motion removal in the actual hardware. Power subtraction is often performed to simulate focus correction in the optical system or to allow power changes to be tracked separately from the rest of the surface deformation. The residual after all terms removed represents how accurately the selected set of Zernike polynomials represent the deformation. This data is represented in tabular form (see Figure 7) and written in files for the specific optical analysis program of choice.

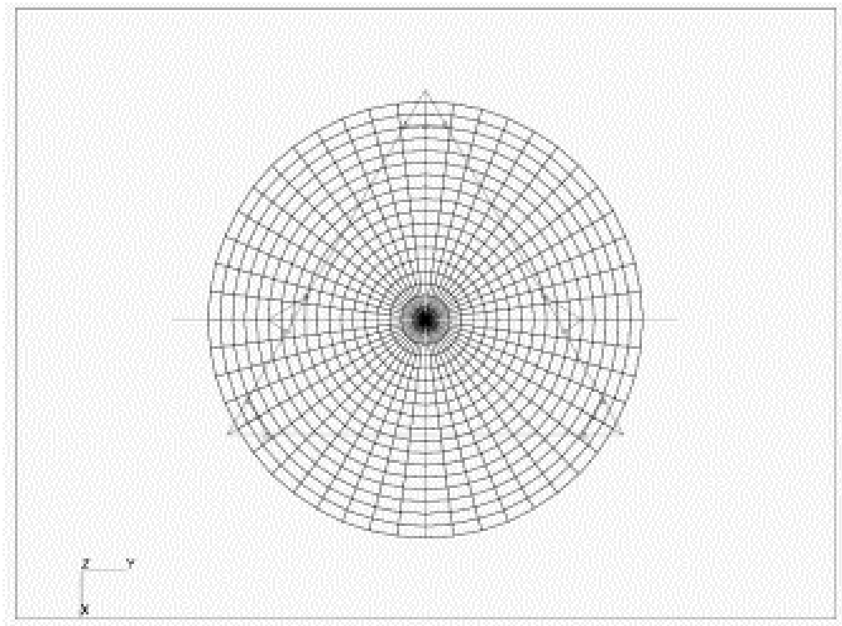


Figure 4. Mirror on Delta Frame

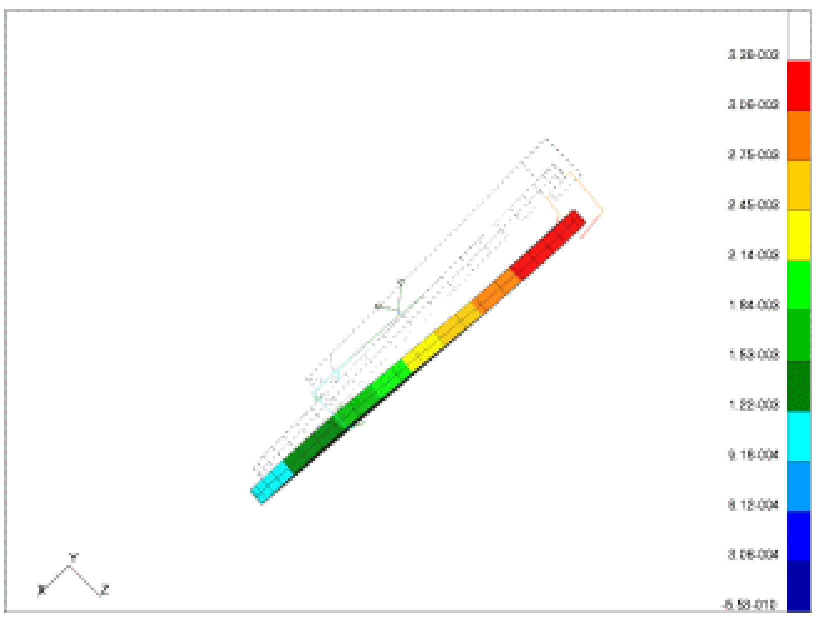
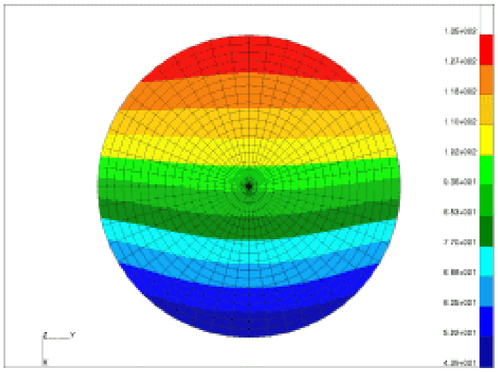
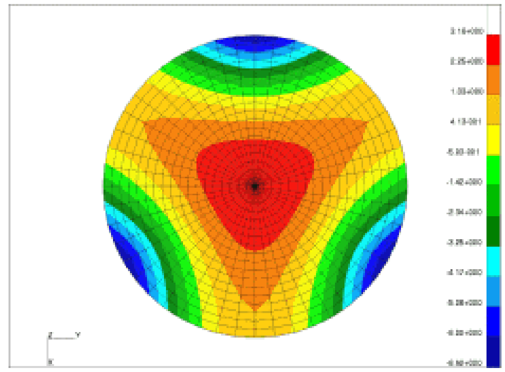


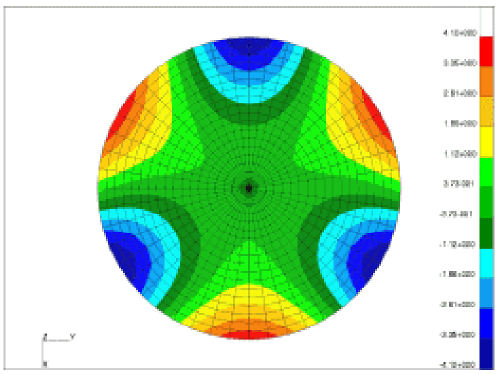
Figure 5. Deformed in 1g



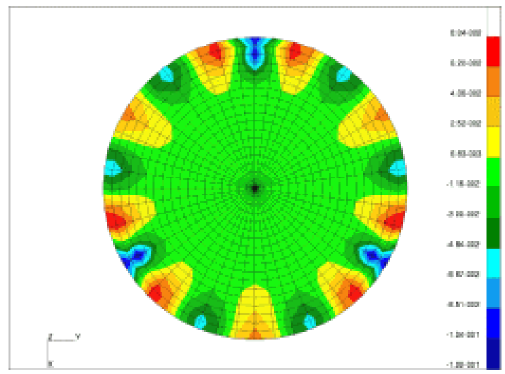
FE Raw Displacement (Normal) RMS=95λ



Best-Fit Plane Removed in SigFit RMS=2.3λ



BFP and Power Removed in SigFit RMS=1.6λ



All Terms Removed in SigFit RMS=0.03λ

Figure 6. Surface Results

Sigmadyne, Inc. SigFit Version=v2003-r1 17-Feb-03 14:02:09

Order K	N	M	Aberration	Magnitude (Waves)	Phi (Deg)	Residual RMS	Residual P-V
			Input(wrt zero)			95.6034	91.1636
1	0	0	Bias	92.29817	.0	24.9243	91.1636
2	1	1	Tilt	49.61448	179.9	2.2775	10.0795
3	2	0	Power (Defocus)	-2.81611	.0	1.5887	8.1731
4	2	2	Pri Astigmatism	.03751	89.8	1.5886	8.1791
5	3	1	Pri Coma	.01434	-180.0	1.5886	8.1862
6	3	3	Pri Trefoil	4.43376	0.0	.2369	1.3379
7	4	0	Pri Spherical	.33960	.0	.1782	1.1849
8	4	2	Sec Astigmatism	.00891	0.0	.1781	1.1890
9	4	4	Pri Tetrafoil	.01092	0.0	.1781	1.1760
10	5	1	Sec Coma	.00038	0.0	.1781	1.1764
11	5	3	Sec Trefoil	.43847	-60.0	.1203	.7565
12	5	5	Pri Pentafoil	.00226	-.1	.1203	.7596
13	6	0	Sec Spherical	-.00403	.0	.1203	.7596
14	6	2	Ter Astigmatism	.00037	-90.0	.1203	.7599
15	6	4	Sec Tetrafoil	.00124	0.0	.1203	.7599
16	6	6	Pri Hexafoil	.42821	-30.0	.0379	.3101
17	7	1	Ter Coma	.00046	.2	.0379	.3102
18	7	3	Ter Trefoil	.00178	60.0	.0379	.3113
19	7	5	Sec Pentafoil	.00237	36.0	.0379	.3104
20	8	0	Ter Spherical	-.00228	.0	.0379	.3136
21	8	2	Qua Astigmatism	.00045	-89.9	.0379	.3133
22	8	4	Ter Tetrafoil	.00055	45.0	.0379	.3129
23	8	6	Sec Hexafoil	.09982	0.0	.0278	.2023

Figure 7. Zernike Table

A special issue that requires attention is that the raw Z displacement does NOT represent the optical sag (Reference 3). If an optic, supported at it's vertex, deforms under an isothermal temperature increase, then the radius-of-curvature increases causing a loss of optical power (see Figure 8). In that figure, the FEA Z displacement is positive whereas the optical sag is negative. The proper sag can be calculated by correcting the Z displacement using the radial displacement and the optical prescription of the surface. SigFit calculates and uses the corrected sag for surface distortion calculations.

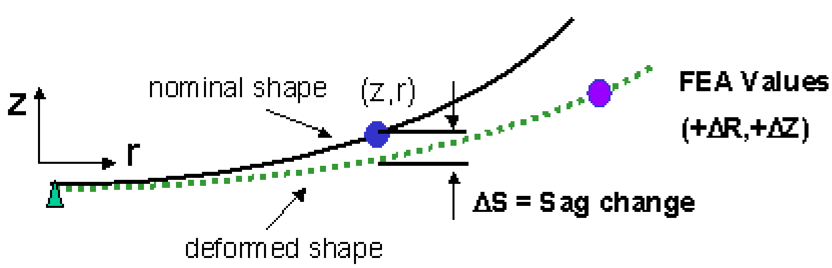


Figure 8. Radial Correction

To write the FEA results in optics format, SigFit will account for the following translation issues:

1) Convert FEA units to optics units, including wavelength of light
2) Convert results to optical coordinate systems, including left-handed rotations
3) Allow use of surface normal (CODE V, OSLO) or axial sag deformations (ZEMAX).

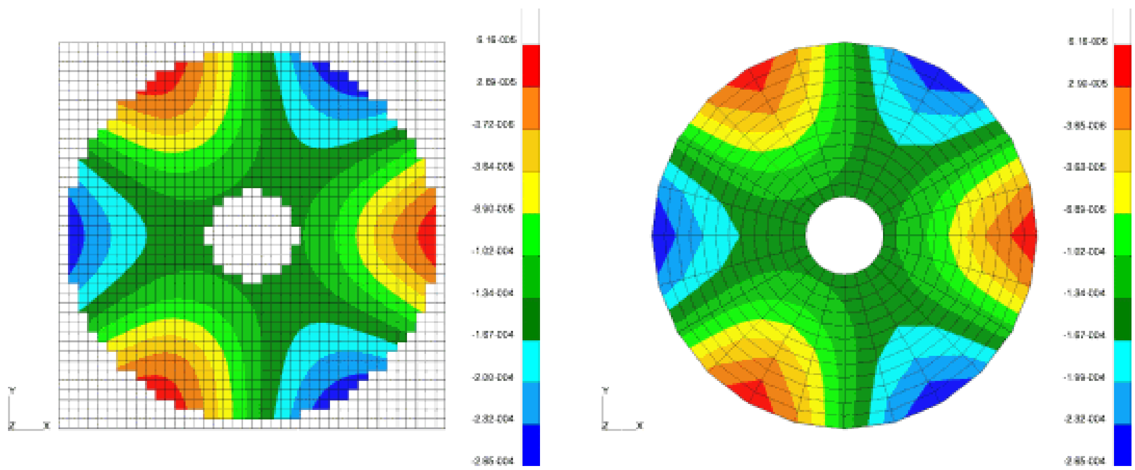
4) Account for apertures and obstructions when processing FEA results

5) Use the normalization and ordering of Zernikes in the target optics code

6) Use area weighting in the fitting process to account for non-uniform FEA meshes

In addition to the optical files created, SigFit will write nodal files in ANSYS format so that results of the SigFit analysis can be displayed on the FEA model.

Higher order surface distortions, such as local mount effects, or quilting sag in lightweight mirrors, are typically poorly represented by Zernike polynomials. In this case, the FEA model results can be converted in SigFit to rectangular arrays (Hit Maps) in the same format as interferometric test data. To calculate the displacement at an array point, SigFit uses FEA shape functions to interpolate (linear or cubic) from the arbitrary FEA mesh (Reference 4). As a data check on the interpolation, SigFit writes a dummy visualization finite element model of the rectangular mesh in ANSYS format so the interpolated results can be compared graphically to the original FEA results (see Figure 9). The resulting Hit Map may be used for comparison of analysis and test on a point-by-point basis. The Hit Map can also be used as a theoretical back-out array, to allow optical fabricators to polish correction factors into the finished optic.



HitMap Contours　　　　FE Model Contours

Figure 9. Interpolated Results

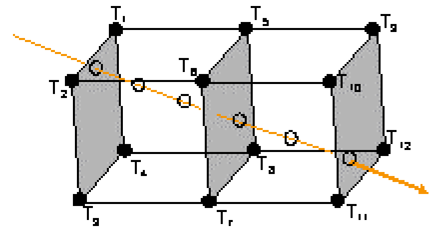
Within SigFit, the interpolation between FEA and Hit Map can run both ways. Thus interferometric test data may be brought into SigFit as a deformed shape and interpolated onto the FEA mesh. The shape may be fit with Zernikes, or compared to FEA results point by point. This could also be used in the adaptive optic analysis module as a deformation to be corrected by actuators.

Thermo-Optic and Stress-Optic Effects

In many lens materials, the index of refraction (n) is a function of temperature (T). A lens subjected to temperature changes will perform differently due to dn/dT effects. An optics program allows the importation of optical-path-difference (OPD) maps to be applied to optical surfaces to account for the thermo-optic index change. Within SigFit, an OPD map is created by integrating the dn/dT effect through each optic. The integration along an arbitrary path requires 3D shape function interpolation from the nodal temperatures (see Figure 10). SigFit writes the OPD map in optical format (Zernike polynomials or Hit Map array) and nodal file format for ANSYS plotting.

Similar effects are caused by stress induced changes to index of refraction. SigFit uses similar integration to calculate stress-optic OPD maps or stress birefringence maps (Reference 5).

$$OPD = \sum_{n=1}^{n=total} \frac{Dn}{Dt} \Delta T_n L_n$$



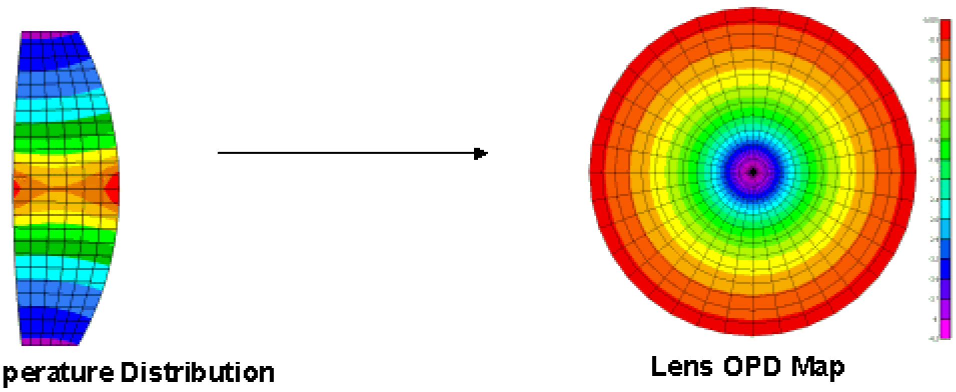


Figure 10. Thermo-optic Effects

A lens system subjected to a laser beam absorbs heat which causes thermo-elastic distortion, thermo-optic OPD effects and stress-optic OPD effects (see Figure 11). The SigFit files were passed to CODE V for system optical analysis. The contribution of each effect is shown as CODE V output (see Figure 12).

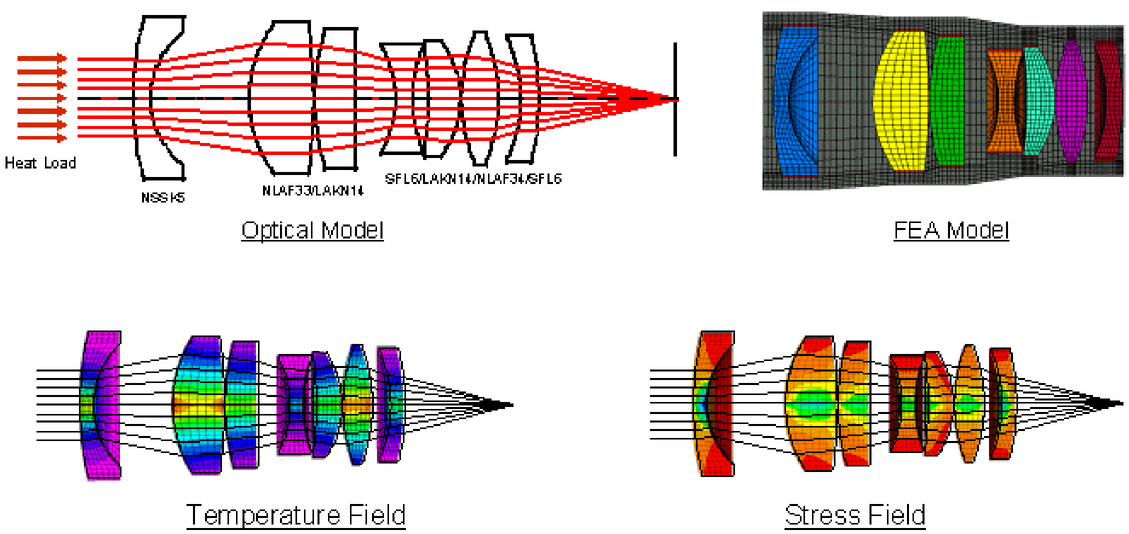


Figure 11. Lens System

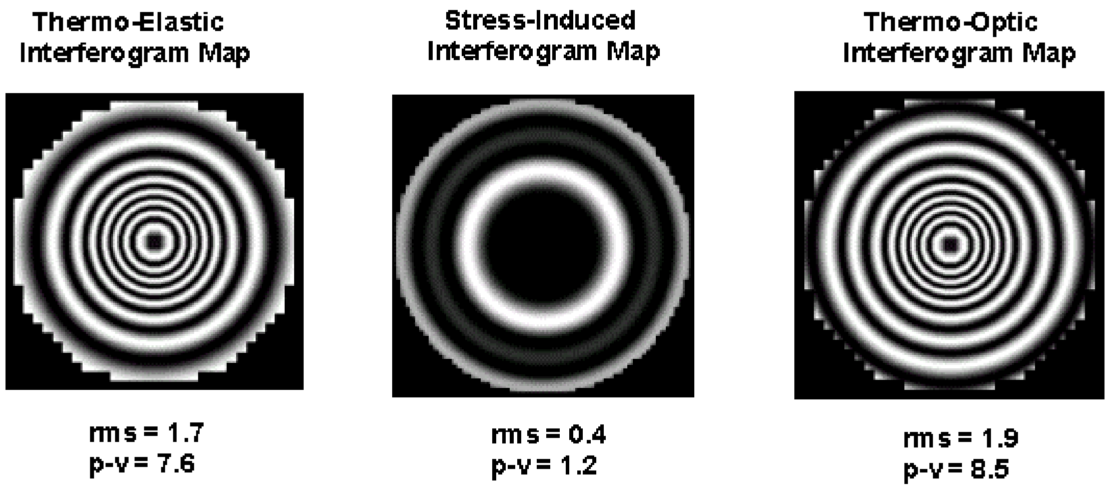


Figure 12. System Wavefront

Adaptive Analysis

The NASA JWST orbiting telescope will have a very large primary mirror which will be subjected to temperature variations causing undesirable distortions. A set of on-board actuators will be used improve the optical performance by correcting the thermo-elastic distortions. SigFit provides an adaptive analysis capability to determine the proper actuator inputs and the resulting performance of the corrected system (Reference 6). The analyst creates a set of influence functions which are surface deflections for unit actuator forces and analyzes for the unwanted distortion. SigFit will solve for the scale factors on actuators to drive the surface RMS to a minimum (see Figure 13). The corrected surface is fit with Zernike polynomials and written in optics format. The corrected surface is also written to ANSYS nodal files for viewing graphically.

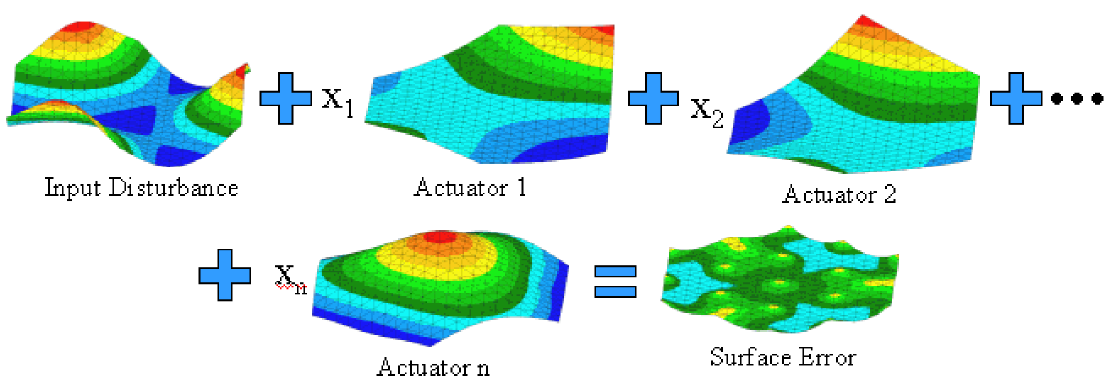


Figure 13. Adaptive Analysis

Dynamic Analysis

If dynamic mode shapes are passed to SigFit, they can be decomposed into rigid-body and elastic distortion components (Reference 7). SigFit can then use modal analysis techniques to conduct harmonic, random or transient analysis. The resulting response will be reported as rigid-body motion and elastic surface RMS motion. This technique is especially useful for random analysis since the resulting nodal displacements from an FEA random analysis have lost all phasing (sign) information. From the FEA random response results, the user cannot distinguish between rigid body (pointing) errors and elastic (wavefront) errors (see

Figure 14). SigFit not only decomposes the response into rigid body and elastic effects, but it lists the percent contribution of each mode to each effect. The modal contributions are valuable for creating design improvements.

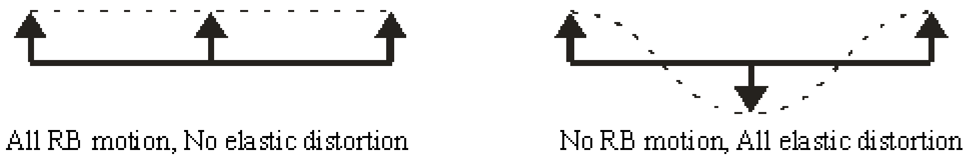


Figure 14. Random Response

System Analysis

For optical systems where the deformations are small, linear superposition may apply. If so, SigFit offers a system response analysis capability (Reference 8). In this approach, the optical analysis program is used to create a set of sensitivity response at a key optical output location such as the exit pupil. These sensitivities are the wavefront response at the exit pupil represented as a Zernike table, due to unit Zernike inputs at each surface. This is a large matrix, but can be created by running a script program. For any given load case (static or dynamic), the system response is calculated by superposition. The system response capability is especially useful in adaptive optics (Reference 9). A simple telescope with an adaptive primary mirror is used as an example (see Figure 15). For a gravity load along the optical axis, the primary mirror, secondary mirror, and exit pupil are shown. If adaptive control is applied to correct only the primary mirror, a significant improvement is shown. However, if the adaptive control is applied to the exit pupil response, much better system performance is obtained. The adaptive primary not only nulls itself, but creates a reverse figure to correct the secondary mirror as well (see Figure 16).

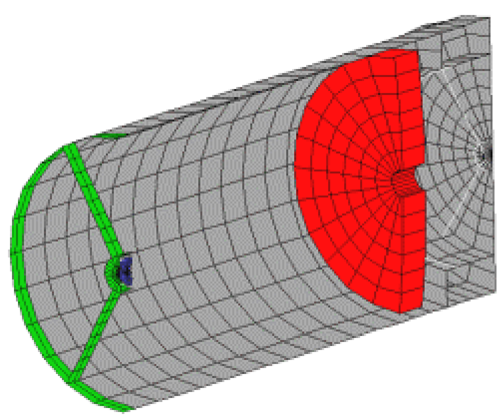


Figure 15. Simple Telescope

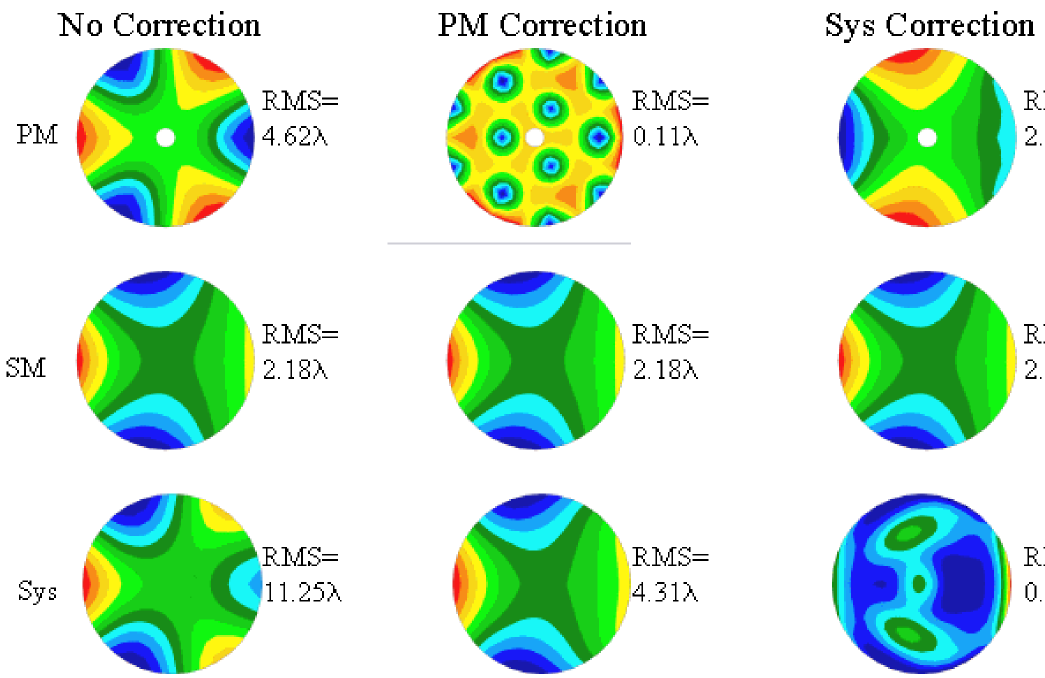


Figure 16. Telescope Correction

System analysis provides a very useful design tool. Using traditional analysis methods, the mechanical engineer must interface with the optical engineer to obtain system level response for every design change (see Figure 17). If the optical design does not change, only the mechanical support structure, the sensitivity matrix discussed above is still valid. The mechanical engineer can cycle through design trades on his own, using system level response as a performance metric (see Figure 18).

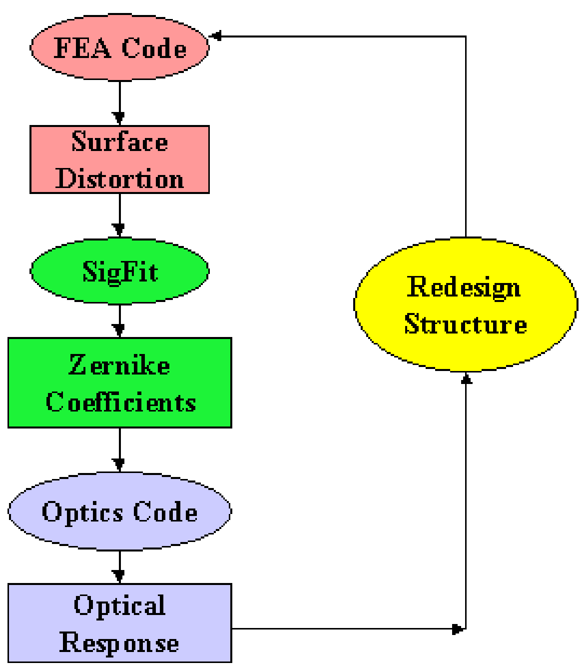


Figure 17. Old Design Process

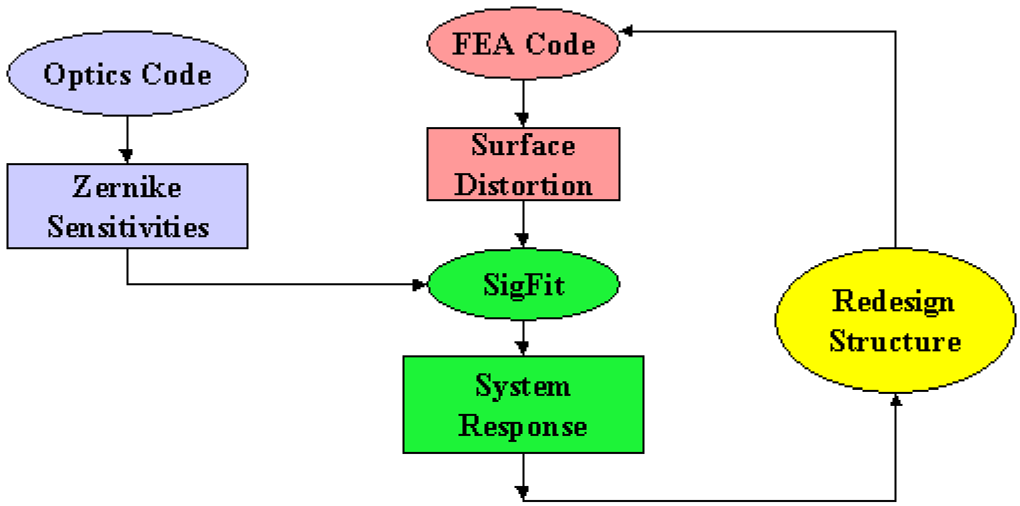


Figure 18. New Design Process

Conclusion

An opto-mechanical interface program for ANSYS has been discussed. SigFit offers many features which make it useful to enhance the overall design process of optical systems. More details are given in the reference papers below as well as the SigFit documentation. The papers and documentation are all available for download from **www.sigmadyne.com**.

References

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