Integrating MD Nastran with Optical Performance Analysis

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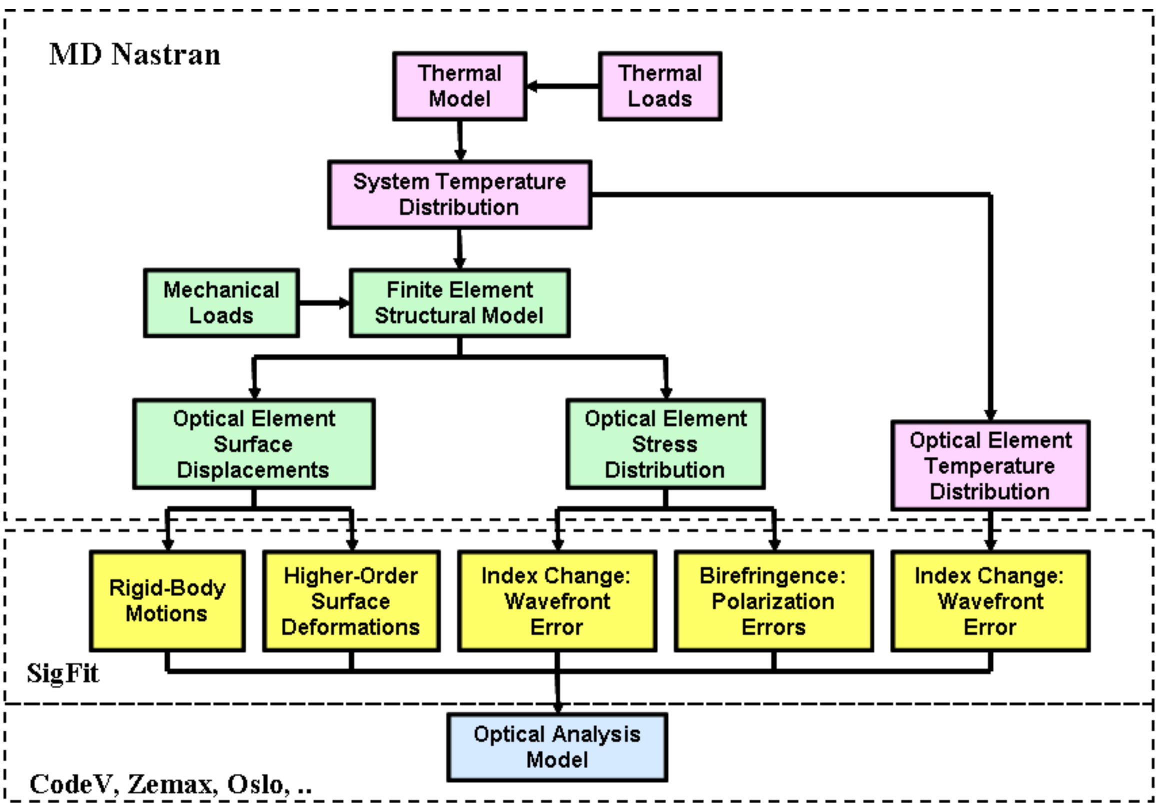
Abstract

The development of products in many industries requires the application of multiple disciplines of engineering in order to obtain useful performance predictions. In the photonics industry performance degradations are caused by various mechanical disturbances such as deformations, motions, temperature changes, and induced stresses within optical components and the metering structures that support them. However, mechanical predictions from finite element tools are not in a readily useable form for use in optical performance analysis tools. This paper discusses the integration of mechanical finite element analysis and optical performance analysis that is required to recast MD Nastran results output into a useable format for some common commercially available optical analysis tools. Specific mechanical disturbance issues include optical surface deformations, thermo-optic effects, and stress-induced birefringence effects. The resulting capability of making optical performance predictions that are tightly linked with mechanical performance predictions from MD Nastran allows opto-mechanical engineers to achieve more aggressive performance requirements. In this paper, an interface program called SigFit will be discussed which converts FEA thermal and structural results from MD Nastran to optical analysis programs CODE V, ZEMAX, and OSLO.

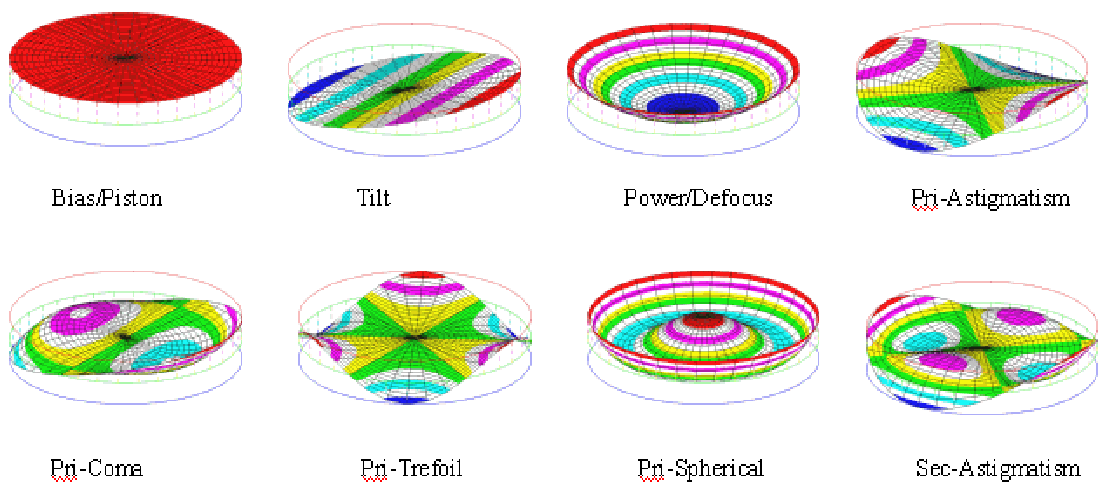
Introduction



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 - **Integrated Analysis**). Thermal and mechanical loads are applied to a finite element model constructed in MD Nastran for the purpose of predicting displacements, temperatures, and stresses in an optical system. These finite element results are subsequently processed by SigFit to generate result files which are importable into commercially available optical analysis tools. These optical analysis tools can then be used to make optical performance predictions which are meaningful to optical engineers yet based on well predicted mechanical behavior of the optical system.

Polynomial Fitting

Zernike polynomials are an infinite set of polynomials (see Figure - **Zernike polynomials**) 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).



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

Zernike polynomials

All optics codes use Zernike polynomials as a common measure of surface deformation. Other polynomials which are supported by SigFit are also used including aspheric, Forbes, XY, Legendre, and Fourier-Legendre. Fourier-Legendre are useful for near-cylindrical X-ray optics (Reference 12).

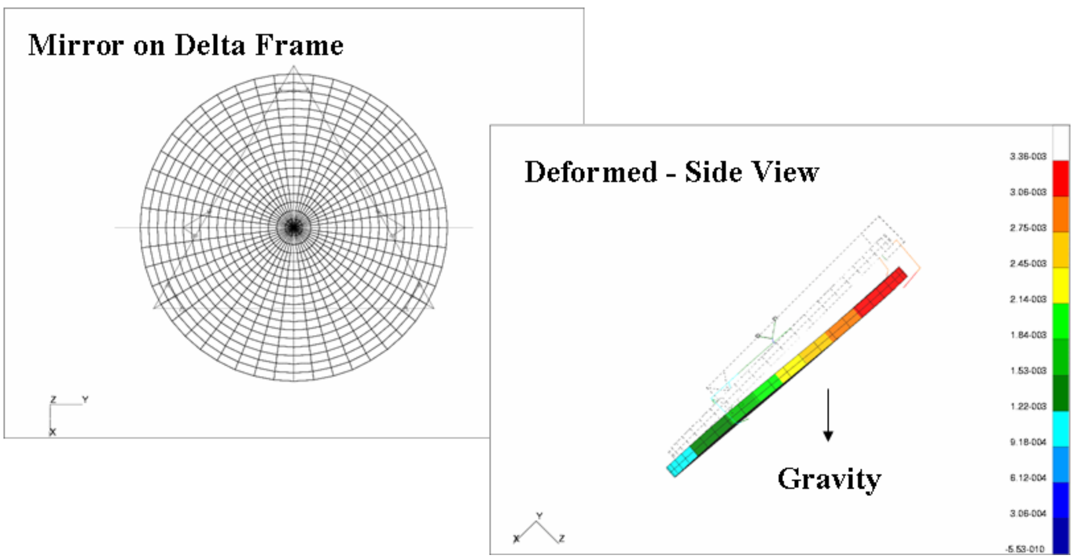
Typical modifications to FEA data required by optics codes include:

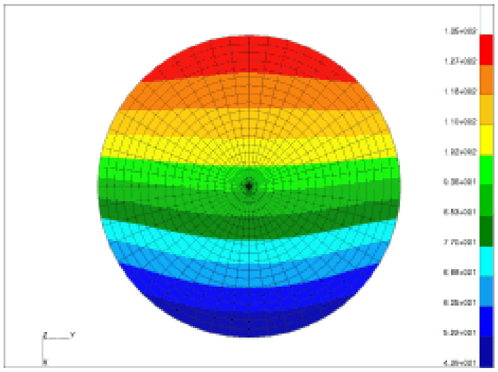
- Condense FEA displacement data into optically meaningful deformations
- Convert units
- Align coordinate systems
- Switch rotations to left-handed system –depending on optical software
- Fit displacements with Zernike (or other) polynomials
- Interpolate results from FEA mesh to a rectangular array

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 which is often represented by Zernike polynomials.

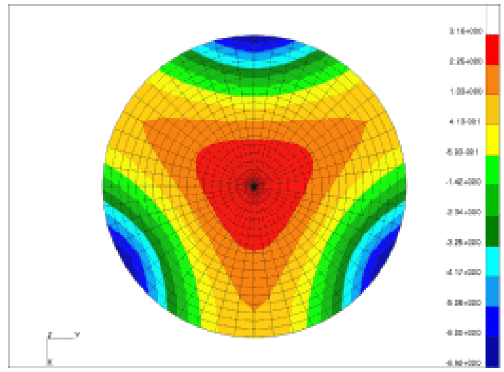
Structural Distortion

Often raw FEA results are dominated by rigid-body motion (see Figure - **Mirror on delta frame**) as in the deformed side view (see Figure - **Deformed in 1g**). 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- **Surface results**). 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 (pointing correction) 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 represents the deformation. This data is represented in tabular form (see Figure - **Zernike Table**) and written in files for the specific optical analysis program of choice.

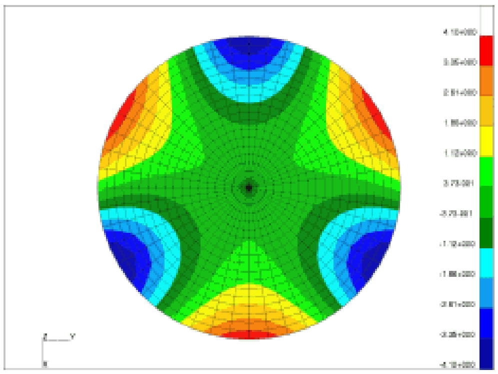




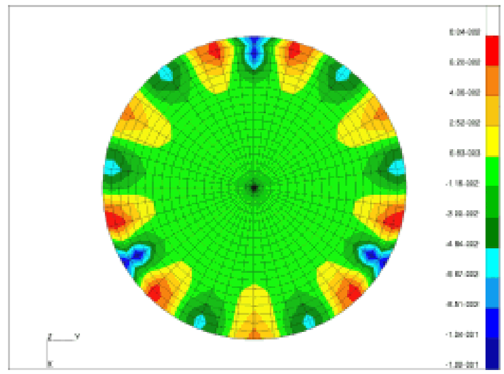
FE Raw Displacement (Normal) RMS=95λ



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

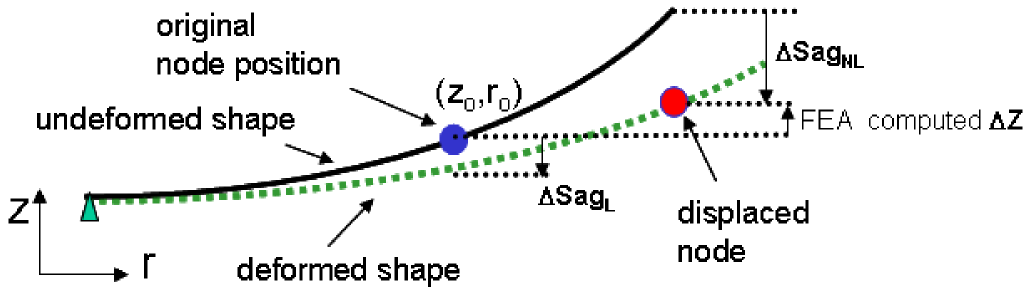
Surface results

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

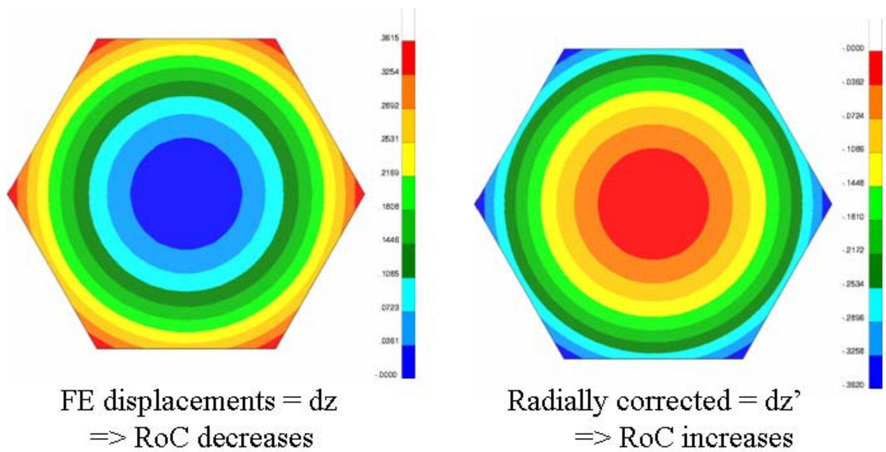
Zernike Table

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 its vertex, deforms under an isothermal temperature increase, then the radius-of-curvature increases causing a loss of optical power (see Figure - **Radial correction**). 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.



Radial correction

A comparison of finite element Z displacement and radially corrected sag (see figure – **Comparison**) shows that the radially corrected sag predicts the increase in radius of curvature, while Z displacement alone does not.



Comparison

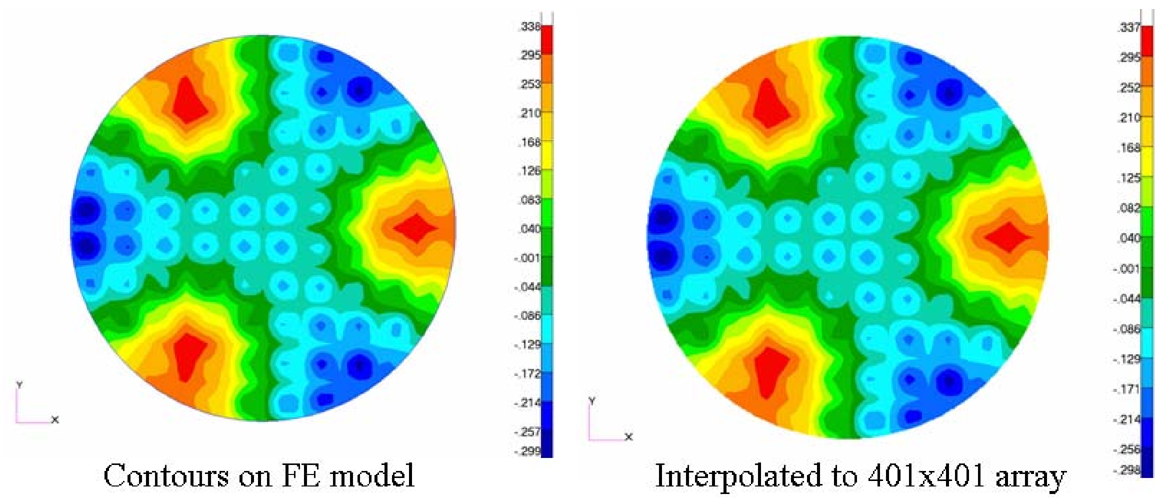
To write the FEA results in optics format, SigFit will account for the following translation issues:

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 (CODE V, OSLO, 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 MSC.Patran or Femap 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 MD Nastran format so the interpolated results can be compared graphically to the original FEA results (see Figure - **Interpolated results**). 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.

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.

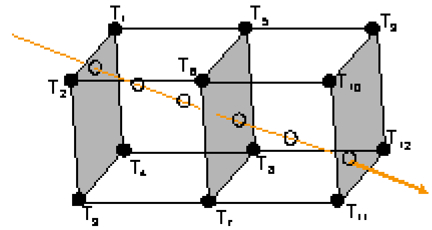


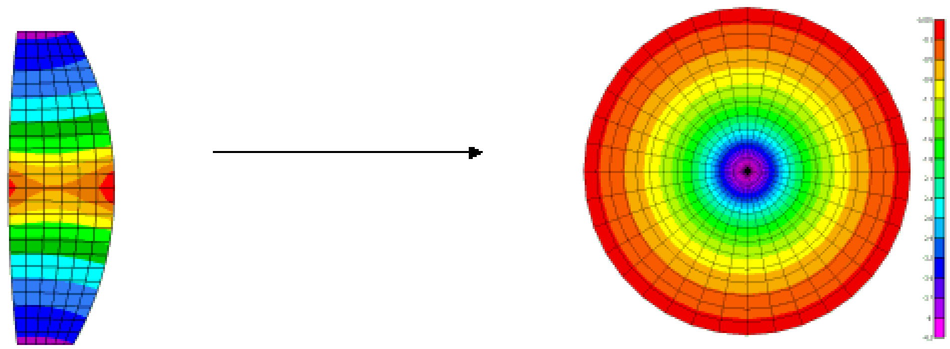
Interpolated results

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 - **Thermo-optic effects**). SigFit writes the OPD map in optical format (Zernike polynomials or Hit Map array) and nodal file format for MD Nastran plotting.

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



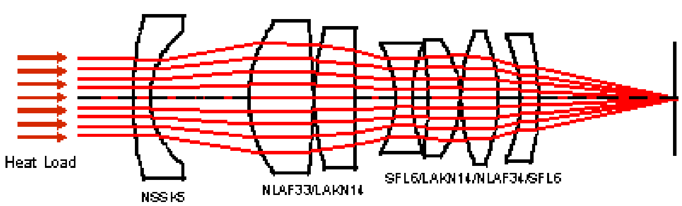


Lens Temperature Distribution **Lens OPD Map**

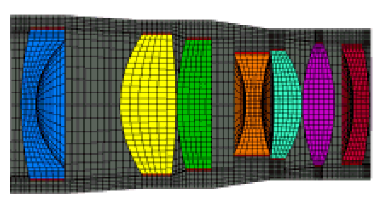
Thermo-optic effects

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).

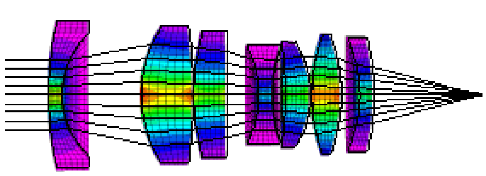
A lens system subjected to a laser beam absorbs heat which causes thermo-elastic distortion, thermo-optic OPD effects and stress-optic OPD effects (see Figure - **Lens system**). The SigFit files were passed to CODE V for system optical analysis. The contribution of each effect is shown as CODE V output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



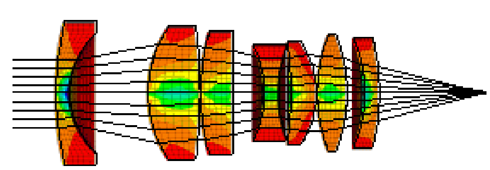
Optical Model



FEA Model

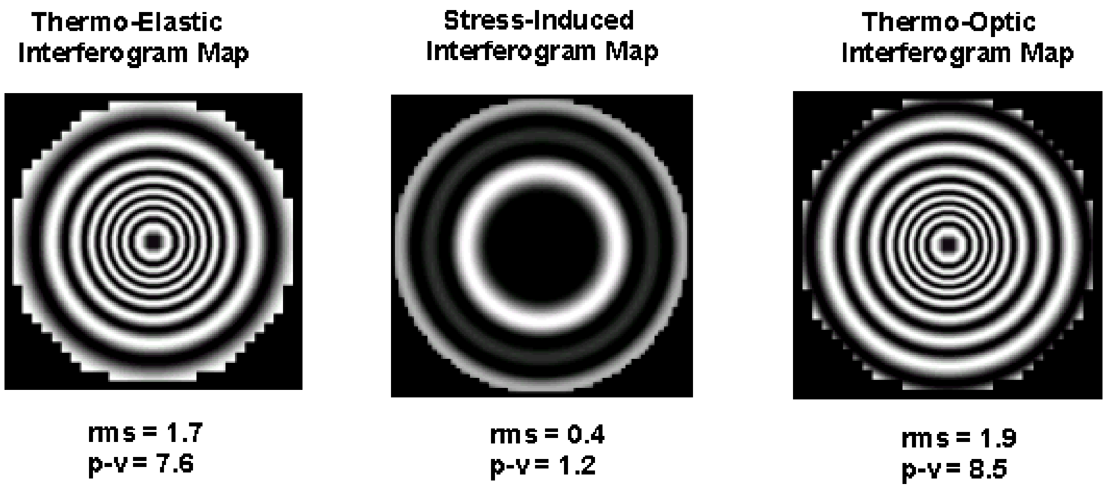


Temperature Field



Stress Field

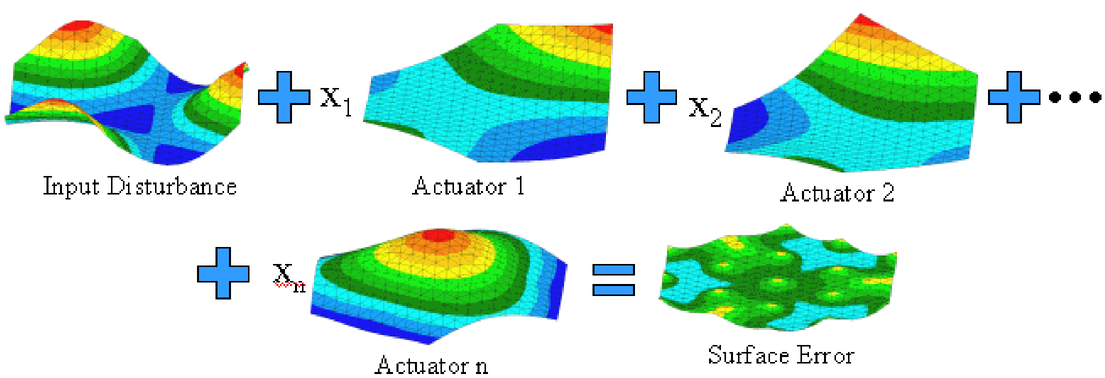
Lens system



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 - **Adaptive Analysis**). The corrected surface is fit with Zernike (or other) polynomials and written in optics format. The corrected surface is also written to MSC.Patran or Femap nodal files for viewing graphically.



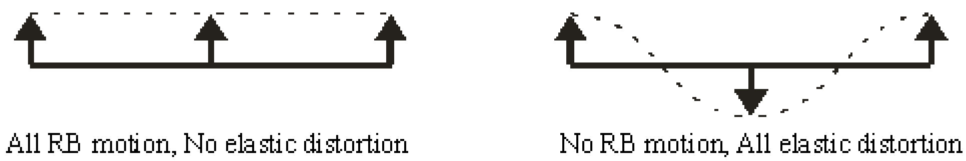
Adaptive Analysis

The best location for actuators is always a design issue. SigFit has a genetic optimization capability to find the best set of actuator locations from a candidate set. (Reference 15)

Adaptive analysis can be used to solve stressed-optic polishing and stressed-lap polishing for actuator forces and resulting correctability. (Reference 13)

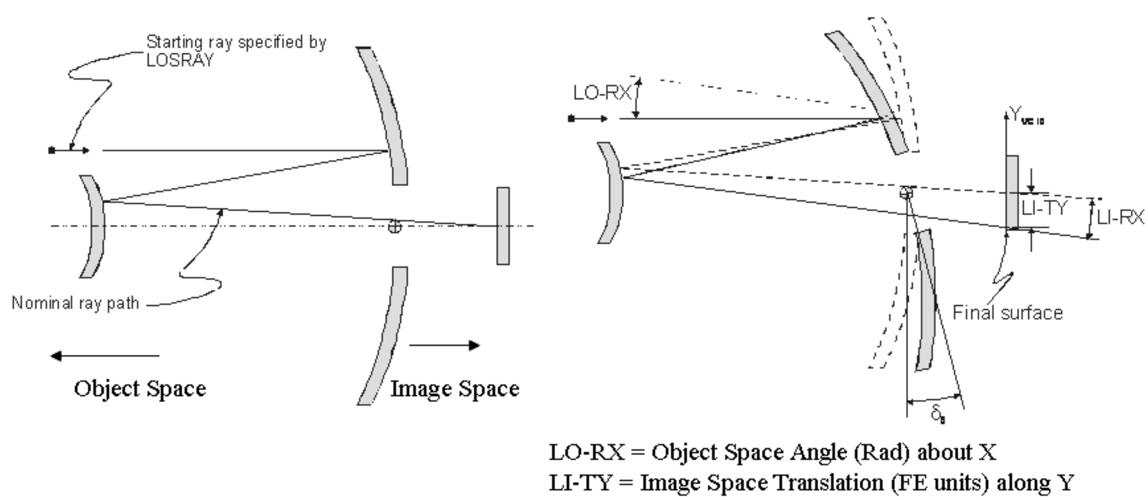
Dynamic Analysis

If dynamic mode shapes from MD Nastran 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 - **Random Response**). 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.



Random Response

In optical systems, line-of-sight (LOS) jitter is a common problem. SigFit has the capability to calculate the LOS coefficients and write them in MD Nastran MPC format. The user has a choice of LOS calculated in object space or image space. (see Figure – **Line-of-Sight**). If the harmonic or random response is calculated in SigFit, the output includes the optical modulated transfer function (MTF) which is a common optical response quantity to evaluate system performance. (Reference 16)



Line-of-Sight

Optimization

SigFit has features to allow optical responses to be used in a structural optimization in MD Nastran SOL 200. For passive optics, a very common design objective is to minimize surface RMS after best-fit plane and power have been removed from the deformation. SigFit will write the DRESP1 and DRESP2 entries to calculate the desired surface RMS which may then be used as an objective or constraint in SOL 200. This is an especially useful feature for designing large light-weight mirrors (Reference 10).

MD Nastran's DRESP3 option allows calls to an external program. SigFit will now write the necessary DRESP1 and DRESP3 entries for SOL 200. During the structural optimization, SOL 200 uses the DRESP3 to execute SigFit to calculate adaptively corrected surface RMS. This new feature will allow SOL 200 to use more complex responses to be used as an objective in the design of an adaptive optical system, such as a telescope with a deformable mirror (Reference 11).

Conclusion

An opto-mechanical interface program for MD Nastran 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**.

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