Analysis technique for controlling System Wavefront Error with Active/Adaptive Optics

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ABSTRACT

The ultimate goal of an active mirror system is to control system level wavefront error (WFE). In the past, the use of this technique was limited by the difficulty of obtaining a linear optics model. In this paper, an automated method for controlling system level WFE using a linear optics model is presented. An error estimate is included in the analysis output for both surface error disturbance fitting and actuator influence function fitting. To control adaptive optics, the technique has been extended to write system WFE in state space matrix form. The technique is demonstrated by example with SigFit, a commercially available tool integrating mechanical analysis with optical analysis.

Keywords: Finite Element, Active Optics, Adaptive Optics, WaveFront Error, System Analysis, Optomechanical

1. INTRODUCTION

1.1 Definition of terms

Active optics are used to correct static or slowly varying phenomenon such as gravity or thermoelastic effects.

Adaptive optics are used to correct rapidly changing effects such as vibrations or atmospheric turbulence.

SigFit is commercial software that interfaces finite element (FE) programs such as Nastran, Ansys, Abaqus, SolidWorks with optical design codes such as CodeV, Zemax, and Oslo.

1.2 Integrated analysis

Increasing performance requirements in high precision astronomical instruments have created the need for increased capability in predicting their performance when subjected to operational environments. Both ground based and space based environments contain thermal variations and vibration disturbances that must be considered in the design development of such high precision systems. Figure 1 shows a flow chart of optomechanical analysis [1].

As shown in Figure 1 disturbances are primarily caused by three physical phenomena: surface deformation, refractive index changes due to stresses in transmissive optics, and refractive index changes due to temperature changes in transmissive optics.

One approach to improving the performance of an optical system subjected to environmental effects is to use active mirror technology. In Figure 2, the primary mirror in the telescope has 18 actuators to control surface shape. Active mirrors can correct distortions and manufacturing errors in the primary mirror. With the use of a linear optics model (LOM), the active mirror can correct other disturbances in the system to improve system level wavefront error (WFE) [2]. In the past this approach was limited due to the difficulty of obtaining an LOM. This paper addresses an automated technique to conduct control of WFE using LOM techniques.

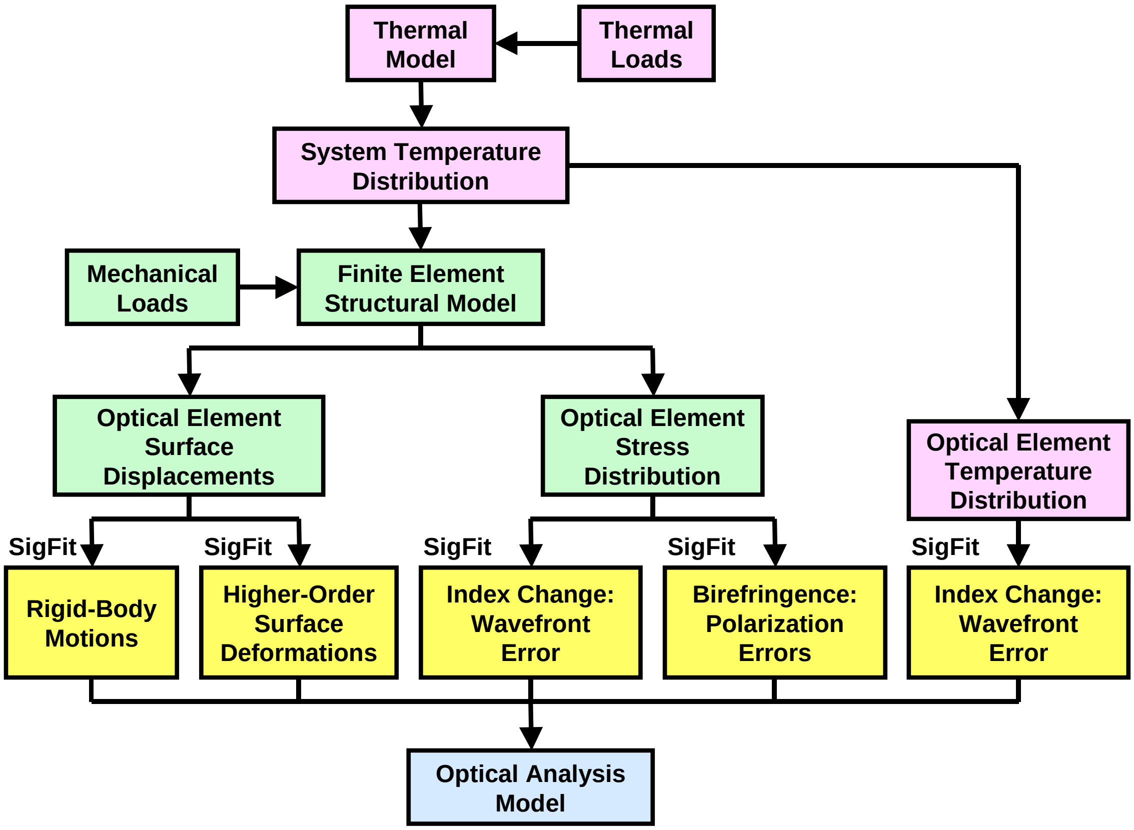

Figure 1. Flow chart of integrated optomechanical analysis.

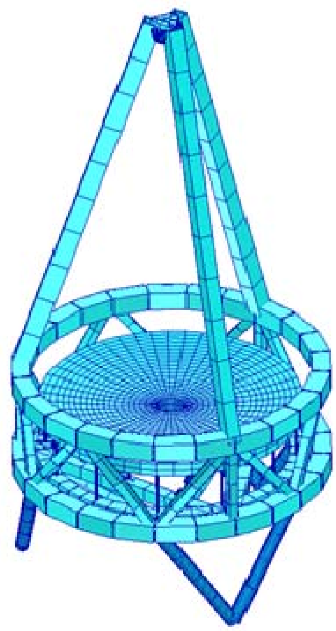

Figure 2: Finite element model of an example telescope with an active primary mirror

2. LINEAR OPTICS MODEL FOR CONTROL OF SYSTEM WAVEFRONT ERROR

2.1 Analysis of Active Optics

The control surface errors of an optical surface in SigFit[3] is described in the following equations.

E = Surface Error

N= the number of nodes,

M = the number of actuator influence functions,

ds'_i = surface deformation at node i,

A_j = actuator input for actuator influence function j,

f_{ji} = surface deformation of actuator influence function j at node i.

$$E = \sum_{i=1}^{N} w_i \left(ds'_i - \sum_{j=1}^{M} A_j f_{ji} \right)^2$$

Taking partial derivatives of E with respect to A results in a linear system.

$$[H]\{A\} = \{F\} \qquad H_{jk} = \sum_i w_i f_{ji} f_{ki} \qquad F_k = \sum_i w_i ds'_i \, f_{ki}$$

Slopes may be included in the least squares error fitting routine [4]. If actuator strokes are limited by fixed bounds or relative bounds described by inequalities, the solution is obtained by an optimization routine. A genetic algorithm is available to choose the best actuator placement [5].

2.2 Linear Optics Model

The linear optics model (LOM) is obtained from the following approach.

1) Create an optical analysis model of the system using a commercial optical design code
2) Within SigFit, read the optics model and choose the type and order of polynomials on each surface
3) SigFit then conducts the following steps automatically
    a. Place a polynomial on surface one
    b. Call the optical code to calculate polynomials at the focal plane
    c. Repeat steps a and b for all polynomials on surface 1
    d. Now repeat steps a, b, c for all surfaces in the model
4) SigFit collects all of the polynomials at the focal plane into a large matrix [S}
5) SigFit now reads a disturbance load case and fits polynomials to the disturbed surfaces [C]
6) System WFE polynomials [Z] are computed from equation 1
7) System WFE RMS is calculated from the RSS of [Z] where w converts magnitude to RMS

$$Z_{ki}{}^{0} = \sum_{n}^{N}\sum_{t}^{T} S_{kt}{}^{n} C_{ti}{}^{n}$$

$$WFE\_RMS = RSS(w_k Z_k^0)$$

In step 3 above, the optics code is called several times to create the full LOM matrix [S]. The matrix [S] is saved to a file for subsequent analyses. Until the optical prescription is changed, step 3 is replaced with a call to read the [S] matrix from file which improves solution time.

The major improvement in the above approach is that the calculation of the LOM matrices is totally automated in SigFit. Since the LOM is created within SigFit, the polynomial ordering, amplitude normalization and radial normalization are all consistent with SigFit's disturbance fitting polynomials. All SigFit features are under user control for selection of polynomials.

2.3 Active control using a linear optics model

The previous section steps can be augmented for active control, by including the polynomial fit to actuator influence function.

Actuator influence fit with polynomial (j) at surface (t) = $B_{jm}{}^{t}$

$$U_{km} = \sum_{t}^{T} S_{kj}{}^{t} B_{jm}{}^{t}$$

$$E = \sum_{k}^{Z} w_k \left(Z_{ki} - \sum_{m}^{M} U_{km} A_m \right)^2$$

As in section 2.1, taking partial derivatives of E with respect to actuator strokes A, provides a linear system of equations.

$$[H]\{A\} = \{F\}$$

As with surface correction, actuator stroke limits and relative limits are allowed. The actuator tolerance analysis available in surface correction is extended to WFE correction.

The accuracy of this approach depends on the quality of the fit to both the disturbances and the actuator influence functions. SigFit reports fitting errors from which the user can judge overall accuracy of the method.

2.4 Comparison of surface correction verses WFE correction

A simple telescope similar to Figure 1 had actuators on the primary mirror (PM). In Figure 3, the first column of plots shows the primary mirror, secondary mirror and system WFE for an uncorrected example. When the PM actuators are used to minimize primary mirror surface error, the results are shown in column two. The system WFE is reduced significantly when the primary mirror is corrected. In column 3, the system WFE is minimized using a linear optics model. In the process, the PM actuators drive the PM surface to the reverse of the SM surface greatly reducing system WFE.

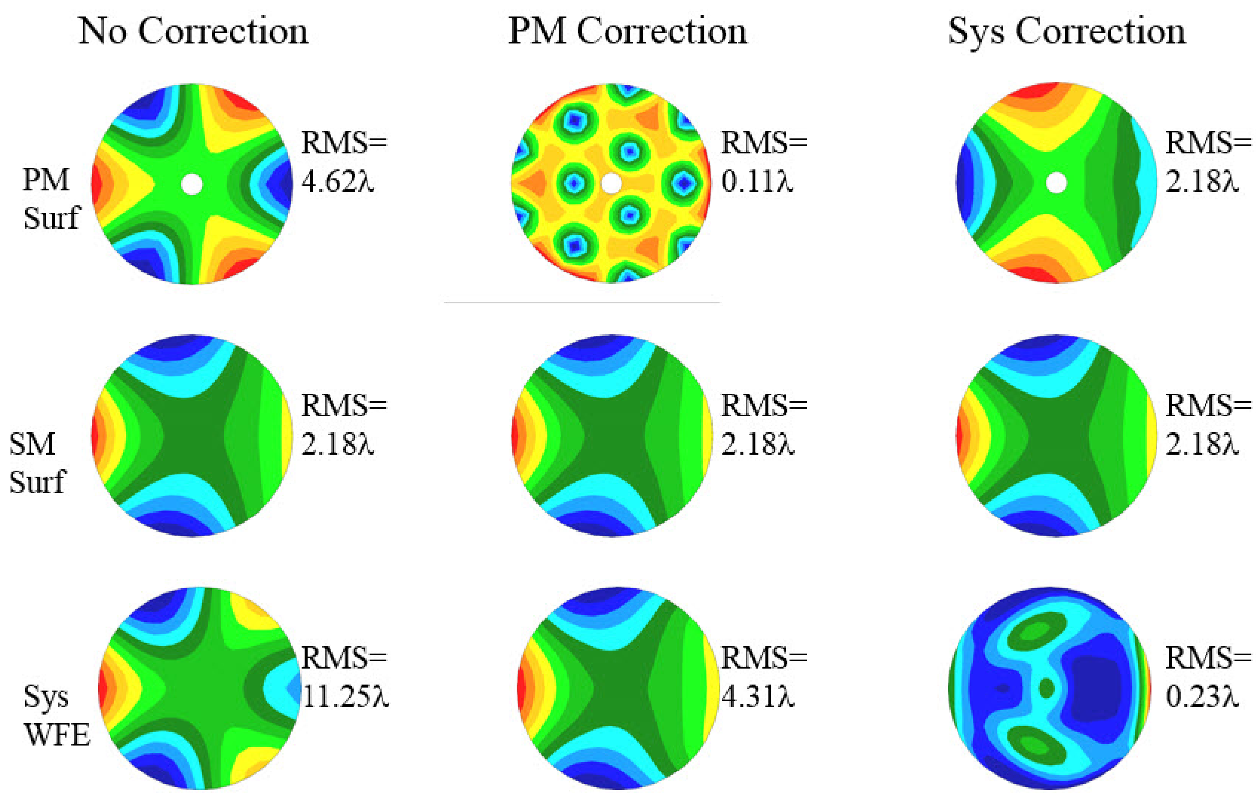

Figure 3: Comparison of surface correction to system WFE correction

3. EXAMPLE TELESCOPE

The simple telscope shown in figure 2 is used to demonstrate the LOM technique.

3.1 Active correction with force actuators

Figure 4 shows 15 force actuators on the primary mirror to control surface figure.. In addtion, each of the 6 flexures have a displacement actuator for rigid body correction. The disturbances are gravity in 2 orientations and an isothermal temperature change of 5 degree C.

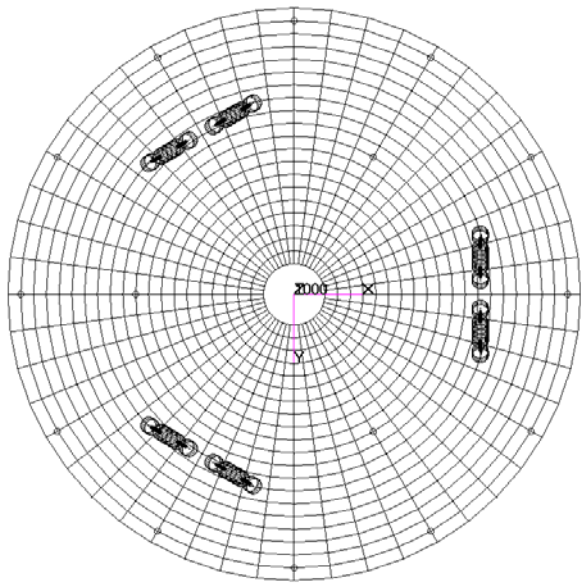

Figure 4: Actuator layout on primary mirror

Using the LOM matrix, SigFit solves for the actuator strokes to minimize the system WFE. Plots of the uncorrected and corrected WFE are given in Figures 5 through 7 for various load cases.

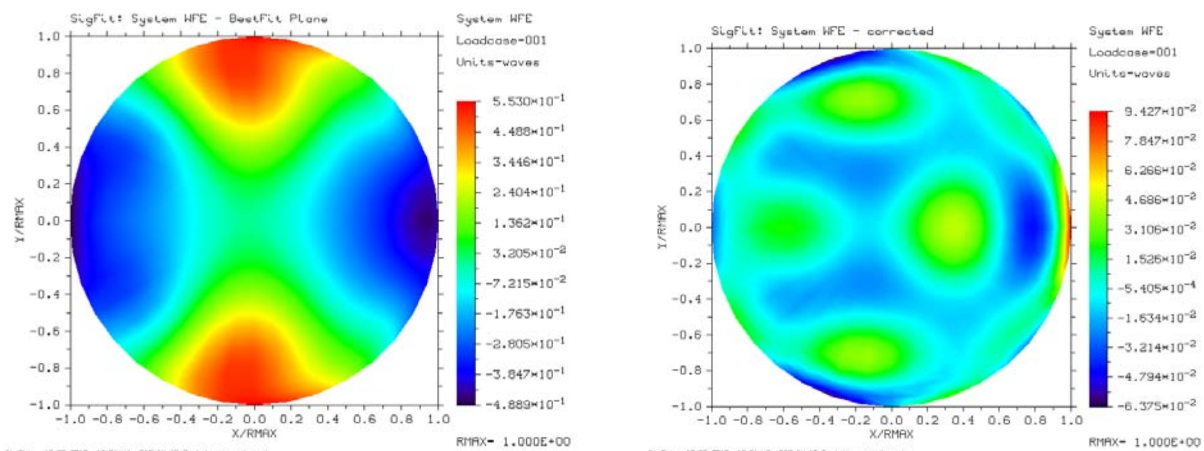

Figure 5: Lateral 1g +X (a) Uncorrected (b) Corrected 93%

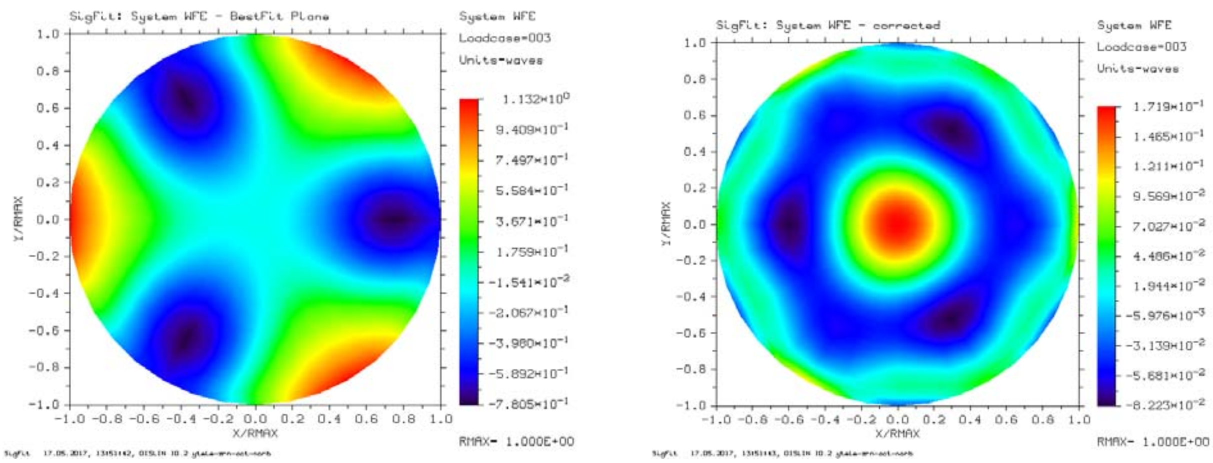

Figure 6: Axial 1g –Z (a) Uncorrected (b) Corrected 89%

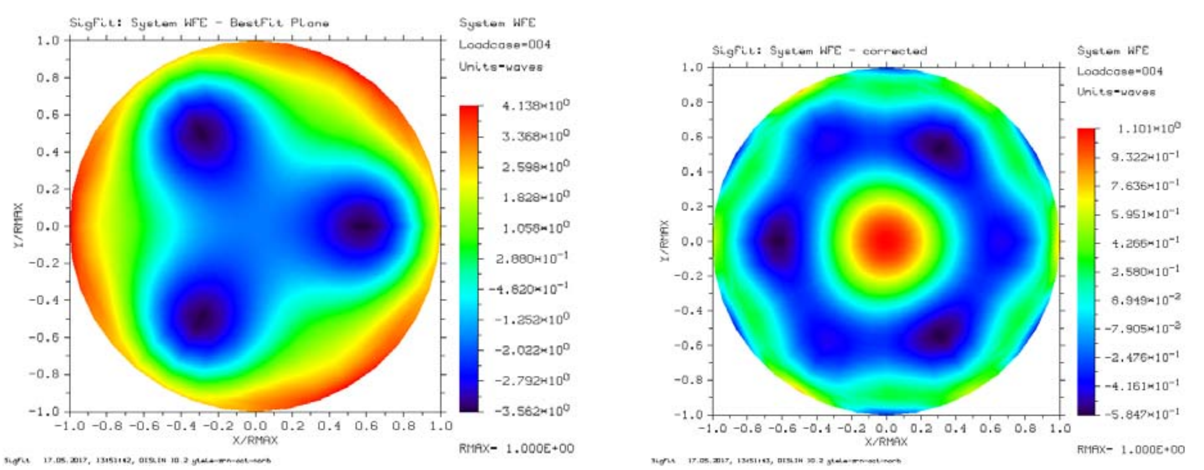

Figure 7: Isothermal +5C change (a) Uncorrected (b) Corrected 83%

The accuracy of the above approach depends on how well the Zernike polynomials fit the disturbances and the actuator influence functions. SigFit provides an error measure on each of those terms and then estimates the overall error on the system WFE. In this example the estimated WFE error was 1.2% on gravity loads and 1.7% on isothermal load.

3.2 Active correction with displacement actuators

The same telescope was modified to replace the 15 force actuators with 15 displacement actuators. In this case, the actuator influence functions are higher order causing more residual error in the Zernike polynomial fit. The actuator influence functions had a fitting error of 5 to 10%. The resulting WFE err estimate increased to 7.5% (up from 1.2% for force actuators).

4. ADAPTIVE MIRRORS

4.1 Adaptive mirrors in transient analysis

Controlling rapidly changing effects with adaptive mirrors is often done using state space with a control algorithm. An approach to using the linear optics model involves fitting the mode shapes and the actuator influence functions with Zernike polynomials. The mode shape distortions of optical surfaces are usually well described by Zernike polynomials. However, the actuator influence functions may not be well characterized by the mode shapes. Requesting residual vectors for actuator forces in the FE natural frequency analysis will augment the mode shapes so that influence functions can be represented very accurately.

$$\begin{Bmatrix} \dot{q} \\ \ddot{q} \end{Bmatrix} = \begin{bmatrix} 0 & I \\ -\Omega^2 & -2Z\Omega \end{bmatrix} \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} + \begin{bmatrix} 0 \\ \Phi_F^T \end{bmatrix} \{f\} \qquad \begin{Bmatrix} \dot{q} \\ \ddot{q} \end{Bmatrix} = [A] \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} + [B]\{f\}$$

$$\begin{Bmatrix} u \\ \dot{u} \\ \ddot{u} \end{Bmatrix} = \begin{bmatrix} \Phi_R & 0 \\ 0 & \Phi_R \\ -\Phi_R\Omega^2 & -2\Phi_R Z\Omega \end{bmatrix} \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \Phi_R \Phi_F^T \end{bmatrix} \{f\} \qquad \begin{Bmatrix} u \\ \dot{u} \\ \ddot{u} \end{Bmatrix} = [C] \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} + [D]\{f\}$$

The second equation is often simplified to just the displacement response.

$$\{u\} = [C]\{q\} = [\Phi_R]\{q\}$$

The advantage that the SigFit LOM approach offers is that the responses are NOT just node displacements, but actual system level response quantities such as:

1) System WFE polynomials (and RMS)
2) System LOS
3) Optical surface average (RB) motions
4) Optical surface Zernike polynomials

An option for Nastran users is a provided DMAP alter which calculates the modal force in the [B] matrix. This is convenient for distributed loads such as acoustic pressure patches.

5. EXTENSIONS

The linear optics model capability has been extended to all SigFit analysis types.

1) Fitting: system WFE polynomials and plots of WFE created
2) Active: corrected system WFE polynomials and plots of WFE created
3) Harmonic Response: system WFE transfer functions are added to output (peaks noted)
4) Transient Response: system WFE time history added to output files (peaks noted)
5) Random Response: system WFE PSD functions, 1-sigma response, and modal contributors added to output [6]

6) State Space equation output: system WFE include in response equations

7) Monte Carlo analysis: tolerance of system WFE to variations added to output

8) Equation writing: system WFE equations written to finite element model (for optimization)

6. CONCLUSIONS

The automated linear optics model approach described above will allow design decisions to be based on the system response rather than individual component responses. The approach has not been used much due to the difficulty in obtaining LOM matrices. The LOM approach has now been totally automated in SigFit making it a convenient design and analysis tool.

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