A thermo-optical analysis method for a space optical remote sensor optostructural system

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Abstract. The space thermal environment is one of the important factors that affect the image quality of a space optical remote sensor (SORS), so discussing the relationship between image quality and the temperature field of a SORS is necessary for thermal control to improve image quality. In this paper, a new thermo-optical analysis method is proposed for the optostructural system of a SORS. Thermal-elastic distortions of all components of an optostructural system, resulting from temperature field changes, cause dimensional instability of the system. This instability is described in terms of changes of position (translations along and rotations around coordinate axes), equation parameters, and roughness of optical surfaces. Then, the theory of homogeneous coordinate transformations and linear fitting of revolving conicoid surfaces are applied to processing of data from finite-element analysis to obtain all the thermally induced dimensional instabilities. Finally, these instabilities were incorporated in optical models (e.g., Zemax) to calculate the thermally induced degradation of image quality (modulation transfer function, wavefront error, etc.). The results of thermo-optical tests suggest that this method is effective.
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Subject terms: space optical remote sensor; optostructural system; dimensional instability; thermo-optical analysis; homogeneous coordinate transformation.

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1 Introduction

As one of the most effective means of observing the earth from space, the space optical remote sensor (SORS) is greatly valued by countries around the world. Among the many factors affecting the image quality of SORSs, temperature is an important one. Because the SORS is a high-precision optical instrument, a small temperature fluctuation may result in a biggish decline in image quality.[1–6] So it is necessary to discuss the relationship between temperature distribution and image degradation for thermal control to improve the resolution and image quality of SORSs.[7–10]

A new thermo-optical analysis method is proposed in this paper, by which the image degradation can be calculated when the temperature field changes in the optostructural system of a SORS, consisting of a primary mirror, a secondary mirror, and their supports.

2 Thermally Induced Dimensional Instability of the Optostructural System of a SORS

A SORS is in a uniform temperature environment in a lab where assembly and testing are carried out. But when on orbit, because of the influences of space vacuum, cold and black background, external heat fluxes, and heat dissipation in the SORS and spacecraft, temperature gradients appear in the SORS and its optostructural system. For the optostructural system, the change of temperature field causes unavoidable thermoelastic distortions in all components; thus, the intrinsic dimensional stability of the optostructural system is compromised.[11–19] In this paper, three kinds of changes are discussed as causes of this thermally induced dimension instability of the optostructural system of the SORS:

1. *The position change of optical elements*: Thermoelastic distortions of all components make optical elements deviate from their original positions. We use three translation values along coordinate axes and three rotation values around coordinate axes to express position deviations of optical elements.
2. *The change of equation parameters of optical elements*: Equation parameters will change a little when an optostructural system changes from one temperature field to another. For a spherical surface, the equation parameter is the radius, and for an aspherical surface, the radius of curvature and the conicoid constant.
3. *The change of surface roughness*.

For a refractive lens, temperature differences would also produce a gradient of the refractive index. For our example, the primary and secondary mirrors were reflective, so that that effect did not occur.

3 Calculation of Dimensional Instability

Usually, the finite-element method (FEM) has been used in engineering to analyze thermoelastic distortion of SORSs.[20–22] The result of finite-element analysis (FEA) is the distortion values of a series of disperse nodes. Here, we use homogeneous coordinate transformation theory and linear fitting of revolving conicoid surfaces to process the FEA data to calculate position changes and function parameter changes of optical elements.

3.1 *Homogeneous Coordinate Transformation Theory and Its Application*

Homogeneous coordinate transformation theory is a method in which an n-dimensional vector is expressed as an $n+1$-dimensional vector. For example, given a point whose Cartesian coordinates are (x,y,z), its homogeneous coordinate expression will be (w_x,w_y,w_z,w), where

$$x=w_x/w, \qquad y=w_y/w, \qquad z=w_z/w. \tag{1}$$

By this theory, a translation (by e, f, g along x, y, z) and a rotation (by θ around x, y, z) of a figure can be expressed by the equations

$$\begin{bmatrix} 1 & 0 & 0 & e \\ 0 & 1 & 0 & f \\ 0 & 0 & 1 & g \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x+e \\ y+f \\ z+g \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix}, \tag{2}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y\cos\theta - z\sin\theta \\ y\sin\theta + z\cos\theta \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix}, \tag{3}$$

$$\begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x\cos\theta + z\sin\theta \\ y \\ -x\sin\theta + z\cos\theta \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix}, \tag{4}$$

$$\begin{bmatrix} \cos\theta-\sin\theta & 0 & 0 & \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x\cos\theta - y\sin\theta \\ x\sin\theta + y\cos\theta \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix}, \tag{5}$$

where (x, y, z) and (x', y', z') are the coordinate representations of points on the figure before and after translating and rotating.[23]

For dimensional instability of an optostructural system resulting from a temperature field change, we can assume that an optical surface translates by amounts e, f, g along x, y, z relative to its ideal position. Thus, if we have known coordinate values of all disperse nodes on the optical surface before and after a change in temperature field, then through a homogeneous coordinate transformation, the total coordinate transform matrix T can be obtained as

$$T=\begin{bmatrix} 1 & -\theta_z & \theta_y & e \\ \theta_z & 1 & -\theta_x & f \\ -\theta_y & \theta_x & 1 & g \\ 0 & 0 & 0 & 1 \end{bmatrix}, \qquad \begin{bmatrix} x_i' \\ y_i' \\ z_i' \\ 1 \end{bmatrix} = T \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}, \tag{6}$$

where

- x_i, y_i, z_i $(i=1,2,...,n)$ are the coordinate values of all disperse nodes on the optical surface before the change
- x_i', y_i', z_i' $(i=1,2,...,n)$ are the coordinate values of all disperse nodes on the optical surface after the change.

Then, based on least-squares fitting, we can solve Eq. (6) to evaluate all unknown parameters of translations and rotations, i.e., the change of position of the optical surface.

3.2 *Linear Fitting for a Revolving Conicoid Surface and Its Application*

As mentioned in Sec. 3.1, by a homogeneous coordinate transformation, we have *filtered* rigid-body displacements of the optical surface. Now, we calculate thermal effects on the equation parameters of a revolving conicoid optical surface.[24]

Suppose a revolving conicoid surface is expressed by

$$x^2=2r_0z-(1+K)z^2, \tag{7}$$

where

r_0 = radius of curvature
K = eccentricity [$K<-1$ for a hyperbola; $K=-1$ for a parabola; $K>-1$ for an ellipse ($K=0$ for a circle)].

Then we have

$$z=c_1x^2+c_2z^2, \tag{8}$$

where

$$c_1=\frac{1}{2r_0}, \qquad c_2=\frac{1+K}{2r_0}.$$

If we define $z=z$, $x_1=x^2$, $x_2=z^2$, then Eq. (8) can be transformed to

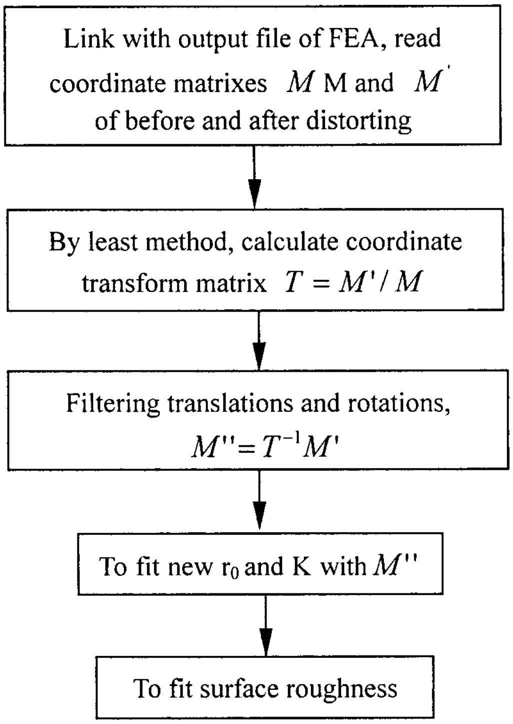

Fig. 1 Scheme of the data-processing program.

$$z = c_1 x_1 + c_2 x_2, \tag{9}$$

which is a binary linear fit to the data $\{(x_{1i}, x_{2i}, z_i),\ i = 1,2,...,n\}$. If we define

$$X = \begin{bmatrix} x_{11} & x_{21} \\ x_{12} & x_{22} \\ \vdots & \vdots \\ x_{1n} & x_{2n} \end{bmatrix}, \qquad Z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix}, \quad \text{and} \quad C = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix},$$

we get $C = (X^T X)^{-1} X^T Z$, and then $r_0 = 1/c_1$, $K = 2r_0 c_2 - 1$.

Compared with nonlinear fitting, circular over-input fitting, spline fitting, and Zernike polynomial fitting, linear fitting of a revolving conicoid optical surface has the advantages of simplicity and good precision.[24,25]

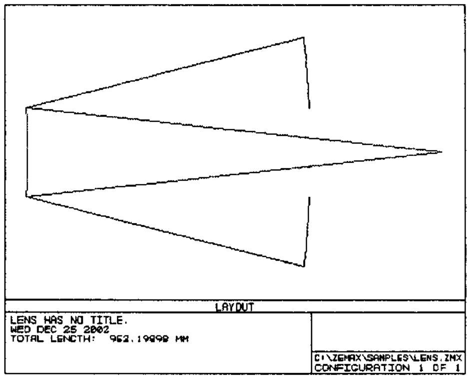

Fig. 2 Optical model of the optostructural system.

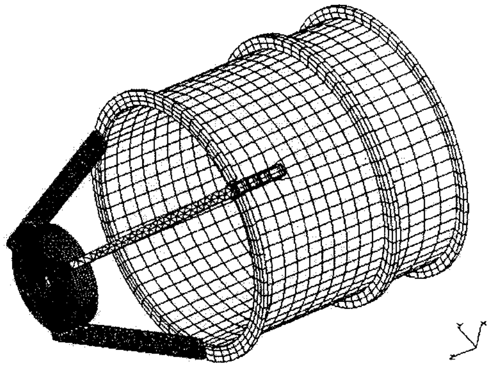

Fig. 3 FEM of the optostructural system.

3.3 *Data-Processing Program*

After solving for the changes of position and equation parameters, we can proceed to calculate the surface roughness, once again by least-squares fitting. Figure 1 gives a scheme of the data-processing program. We realized it with Matlab.

4 Evaluating of Image Degradation

In Sec. 3, thermal effects on the dimensional stability of the optostructural system of a SORS and the corresponding calculation process were introduced. For a given reference temperature field and temperature field change, the changes of position, equation parameters, and surface roughness of all optical surfaces in an optostructural system could be carried out. Fortunately, these values can be directly put into optical analysis software (e.g., Zemax) to calculate very conveniently the modulation transfer function (MTF), wavefront error (WFE), etc. Thus, the image degradation resulting from the change of temperature field is obtained.

5 Results of Analysis and Testing

The optostructural system of a practical advanced SORS was taken as an example to do thermo-optical analysis according to the method described. Its optical system consisted of two aspherical mirrors: the primary and secondary mirrors. The optical model built in Zemax software is shown in Fig. 2. Figure 3 shows the FEM, as realized in Ideas software, of the optostructural system, which con-

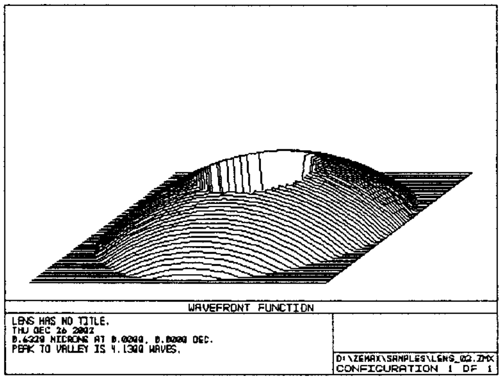

Fig. 4 WFE in state 1. Peak-to-valley distortion due to temperature change was 4.13 waves.

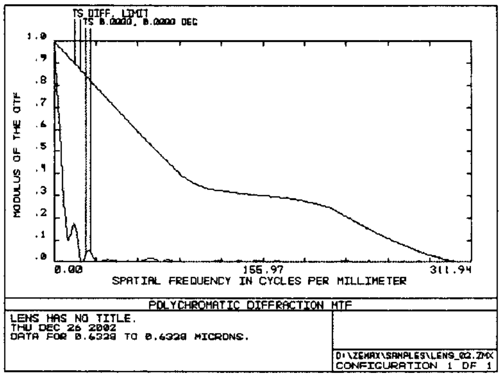

Fig. 5 MTF in state 1. Upper curve: diffraction-limited MTF. Lower curve: MTF decreased by temperature change.

sisted of the primary mirror subassembly, the secondary mirror subassembly, and their supports. (The bigger one, with a hole in its central section, is the primary mirror, and the smaller one is the secondary mirror.)

5.1 *Thermo-optical Analysis Results*

In the thermo-optical analysis, the normal temperature was set as the reference temperature, and three other temperature states were examined. State 1 was 5 K hotter and in vacuum, state 2 was 10 K cooler and in vacuum, and state 3 had a circumferential temperature gradient on the bench of the primary mirror. The WFE and MTF were the parameters selected to express image degradation. For example, Fig. 4 and Fig. 5 show the WFE and MTF of the optostructural system in state 1. The corresponding results for the other temperature states are omitted from this paper for reasons of space. We found that the image quality was greatly degraded by the change in temperature field.

For proper comparison with thermo-optical tests, in Zemax we adjusted the position of the focal plane to optimize the optostructural system to achieve a maximal MTF for every temperature state, and then recorded the displacement of the focal plane relative to original position. Figures 6 and 7 show the WFE and MTF after optimizing in state 1.

The analysis results are listed in Table 1. The value 38.5 lp/mm was chosen for the characteristic space frequency, because that value was used in the subsequent thermo-optical tests.

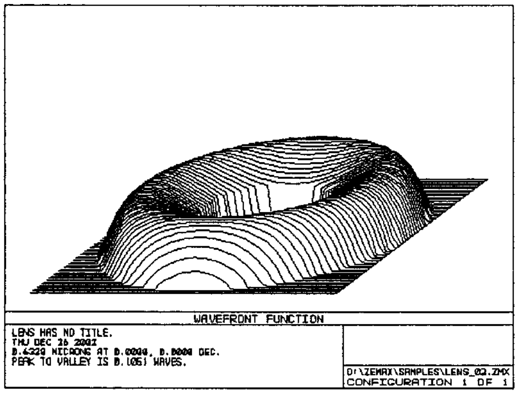

Fig. 6 WFE after optimizing in state 1. Peak-to-valley distortion was 0.1051 waves.

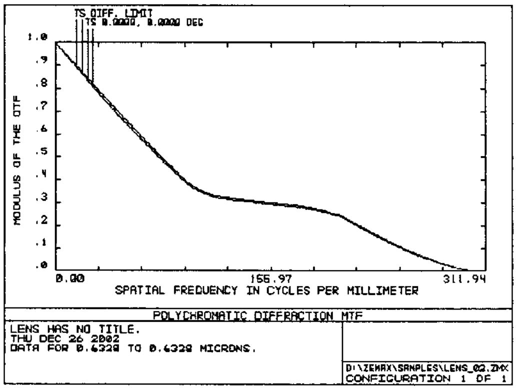

Fig. 7 MTF after optimizing in state 1 (very close to the diffraction-limited MTF).

5.2 *Thermo-optical Test Results*

Thermo-optical testing was performed in a thermal vacuum chamber. After the SORS was mounted in the chamber, the chamber was evacuated to 10^{-4} Pa. Subsequently, the SORS was tested and adjusted in the condition of normal temperature and vacuum to ensure a good reference state. Then, the SORS was changed to a new temperature state.[26–28] In this new state, the image quality was measured, and we found it to be distinctly degraded.

In order to analyze thermal effects on image quality quantitatively, we refocused the SORS to get a maximal MTF, and recorded the displacement of the focal plane relative to original position. This displacement was compared with the one obtained from thermo-optical analysis to see if they were consistent. The test results are listed in Table 2.

Comparing the results of thermo-optical analysis with those of the tests, we find that in state 1 and state 2, the displacements of the focal plane were almost equal, and the errors were 8.8% and 2.2%, respectively. In state 3, the displacements were opposite in sign, but they were close to zero.

Because the thermo-optical test of the SORS was very complicated and accurate, we think that the environmental disturbances in the lab (for example, the vibration of the vacuum pump) were the primary source of error. So the thermo-optical analysis method proposed is effective.

Table 1 The results of the thermo-optical analysis.

State number	Displacement of focal plane (mm)	MTF
1	0.848	0.68
2	1.460	0.65
3	0.016	0.65

Table 2 The results of the thermo-optical test.

State number	Displacement of focal plane (mm)	MTF
1	0.773	0.729
2	1.428	0.730
3	−0.096	0.728

6 Conclusion

Thermo-optical analysis has been very important and indispensable for the research and development of SORSs. A new thermo-optical analysis method for the optostructural system of a SORS has been proposed in this paper. First, the thermal effects on dimensional instability of the optostructural system of a SORS were discussed, and three kinds of changes were used to express this thermal-induced dimensional instability. Second, homogeneous coordinate transformation theory and linear fitting of a revolving conicoid optical surface were applied, using FEA data processing, to evaluate the thermally induced dimensional instability. Last, those instability values were imported into Zemax to evaluate the degradation of image quality. This analysis method was applied to the thermo-optical analysis of a practical advanced SORS.

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