A novel method of error analysis for opto-mechanical system based on space and time stability

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A novel method of error analysis for opto-mechanical system by considering issues of the space and time stability is proposed. According to the theory of error transfer model and the system stability requirements, the temporal parameter is introduced as the dynamic compensate to reflect the structure random response influencing the position precision in the period of working time. The error transfer model originated from our method is also put forward. Moreover, the simulation is used to analyze the error of spatial filter system in Shenguang (SG) II facility. The results show that the method can more effectively deal with the target position error induced by the system structure, and it also provides a dynamic error analysis method for the high power laser facility and other great science projects.

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In the high power laser facility, the opto-mechanical system is the optic and opto-mechanical support hardware which is necessary to transport the laser beams through the system from the laser drivers to the target[1]. In order to satisfy the main laser beam accurately positioned, the facility should have a high precision, and even more have a high stability before and during a shot. It demands the system providing a stable platform for the optical elements and alignment process[2,3]. Therefore, the error analysis method is generally used to analyze the beam position error which is induced by the structures in the opto-mechanical systems such as in the Shenguang (SG) II facility.

Of many literatures, the general error analysis method is to analyze the translation and angle error of optical element in the system, then further to obtain the total error of the system. Subsequently, by comparing the total error with the budget error, one can confirm the performances of the system stability[3,4]. For this method, the error result only shows the static error induced by the system structure, and without considering the distortion issues of a structure during the working time. Actually, to the long time work system, we more concern the time stability which often expresses the dynamic characteristics of a system. Under these circumstances, a new method for error analysis of opto-mechanical system based on the space and time stability is proposed. Combined with the theory of general error transfer and the stability requirements of the system, the temporal parameter is introduced as the dynamic compensation to reflect the structure random response inducing the error to the positioned error in work time.

Now let us describe our method and give some examples. Firstly, as we know, the stability of an optical element is a random variable so the theory of random error can be used to analyze the error. Usually, the standard deviation σ is used to reflect random error. Then the combination of the random errors is mainly to indicate the combination of the precision of the parameter σ at a certain probability.

For one system, the stability requirements of system include space stability and time stability. By considering the question of transferring of the random error, there exists m objects which can be measured directly. Here we suppose some variables of spatial parameter marked as x_1, x_2, $\cdots$, x_m and the corresponding random error and standard deviations indicated as δ_{x_1}, δ_{x_2}, $\cdots$, and σ_{x_1}, σ_{x_2}, $\cdots$, σ_{x_m} respectively. Symbols t_1, t_2, $\cdots$, t_m are the variables about temporal parameters. Symbols δ_{t_1}, δ_{t_2}, $\cdots$, δ_{t_m} and σ_{t_1}, σ_{t_2}, $\cdots$, σ_{t_m} represent the random error and standard deviations of t_i $(i = 1, 2, \cdots, m)$, respectively. Variable y is an indirect measurement value, and the random error and standard deviation of y are marked as δ_y and σ_y, respectively. So y is a continuously differentiable function with x_1, x_2, $\cdots$, x_m and t_1, t_2, $\cdots$, t_m, which is expressed as

$$y = f(x_1, x_2, \cdots, x_m, t_1, t_2, \cdots, t_m). \tag{1}$$

The complete differential function of Eq. (1) is

$$\mathrm{d}y = \frac{\partial f}{\partial x_1}\mathrm{d}x_1 + \frac{\partial f}{\partial x_2}\mathrm{d}x_2 + \cdots + \frac{\partial f}{\partial x_m}\mathrm{d}x_m + \frac{\partial f}{\partial t_1}\mathrm{d}t_1 + \frac{\partial f}{\partial t_2}\mathrm{d}t_2 + \cdots + \frac{\partial f}{\partial t_m}\mathrm{d}t_m. \tag{2}$$

According to the theory of the error transfer, the transferring of random error can be expressed as[5]

$$\sigma_y^2 = \sum_{i=1}^{m}\left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2 + \sum_{i=1}^{m}\left(\frac{\partial f}{\partial t_i}\right)^2 \sigma_{t_i}^2 + C, \tag{3}$$

where

$$C = 2\sum_{1\leq i\pi k\leq m}\left(\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_k}\rho_{ik}\sigma_{x_i}\sigma_{x_k}\right) + 2\sum_{1\leq j\pi k\leq m}\left(\frac{\partial f}{\partial t_j}\frac{\partial f}{\partial t_k}\rho_{jk}\sigma_{t_j}\sigma_{t_k}\right) + 2\sum_{1\leq i\pi j\leq m}\left(\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial t_j}\rho_{ij}\sigma_{x_i}\sigma_{t_j}\right),$$

and ρ_{ik} is the correlation coefficient of variables x_i, x_k. We assume that the value of correlation coefficient ρ_{ik} is zero if the random error δ_{x_i} $(i = 1, 2, \cdots, m)$ among variable x_i is interrelated. And it is same to the correlation coefficient ρ_{jk}. For the correlation coefficient ρ_{ij}, it is irrelevant between the spatial and temporal parameters, so ρ_{ij} is also thought as zero.

Of the stability analysis for the high power laser facility, each optical element is frequently assumed as an independent measured object. So the stability of optical element to the position error is independent or weak correlation. For the reason of analyzing the transfer model more easily, we must discuss Eq. (3). At first, it is assumed that all of the random error of variables is irrelevant both in the spatial and temporal parameters, so the values of the correlation coefficients ρ_{ik} and ρ_{jk} are zero, namely, C is zero. Then Eq. (3) can be simplified as

$$\sigma_y^2 = \sum_{i=1}^{m} \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2 + \sum_{i=1}^{m} \left(\frac{\partial f}{\partial t_i}\right)^2 \sigma_{t_i}^2. \quad (4)$$

The first part of Eq. (4) represents the static error related to the space stability. According to the theory of error transfer, it can be expressed as[3,4,6]

$$\sigma_{\mathrm{s}}^2 = \sigma_1^2(x_1) + \sigma_2^2(x_2) + \cdots + \sigma_m^2(x_m), \quad (5)$$

where σ_{s} is the target position error of the system; σ_i is the position errors of the optical elements with serial number i or units induced by the structure distortion. The target position error of the system originated from Eq. (5) can be shortened by changing the structure of the system, and it can be also further corrected.

Further analyzing the second part of Eq. (4), it is shown that random response impacts the position error of the system in the period of the working time, and it is a kind of dynamic errors. For a system with a long time working, we should more concern on the dynamic errors during the whole working time. Normally, the dynamic errors can be expressed as the random response of the system influencing on the position errors in the domain of work frequency of the system, and the equivalent values can be deduced as follows.

Based on the above analysis, and from Eq. (4), the dynamic errors in the high power facility will exhibit a concept of the time stability. In order to get the equivalent values, we assume that $h(t)$ is the displacement response of the system induced by the random disturbances of the circumstances and $F(s)$ represents the system transfer function. The function $H(s)$ denoted the Laplace transform of $h(t)$. Let $X(t)$ denote the displacement of the system induced by the exciter $h(t)$. The function $X(s)$ is the Laplace transform of $X(t)$. There is

$$X(s) = F(s)H(s). \quad (6)$$

The value of the second part of Eq. (4) can be obtained from Eq. (6), which is equivalent to

$$\sigma_{\mathrm{d}}^2 = X_1^2(t_1) + X_2^2(t_2) + \cdots + X_m^2(t_m), \quad (7)$$

where σ_{d} is the system dynamic error including the compensation for the time stability. σ is the budget of the position error of the beam in the shot experiment. From Eqs. (4), (5), and (7), we can deduce the control error of the system stability

$$\sigma_y^2 = \sigma_{\mathrm{s}}^2 + \sigma_{\mathrm{d}}^2 \leq \sigma^2. \quad (8)$$

Figure 1 shows the sketch of the error control in time domain. Figure 1(a) illuminates the static error which only considers the case of the space stability by using the general error analysis method. In this analysis, the curve of σ_y shows some fluctuates. At the same time, Fig. 1(b) shows that the errors comprises of the static and dynamic errors. The dynamic compensation error will contribute to the system error by adding σ_{d} to the center of the vertical coordinate.

Other instances of Eq. (3) are given by considering the correlation coefficients ρ_{ik} and ρ_{jk} zero not simultaneously. So Eq. (8) can be modified as

$$\sigma_y^2 = \sigma_{\mathrm{s}}^2 + \sigma_{\mathrm{d}}^2 + C \leq \sigma^2. \quad (9)$$

We can choose a certain coefficient C to reflect its contribution to σ_y^2 by analyzing the relation of the direct measurement variables. It is shown by shifting C distantly to the vertical coordinates. Here it is worth explaining that we need not further to discuss this issue in the following.

In the inertial confinement fusion (ICF) facility, the amplifiers and spatial filters are the most important elements. The main role of the amplifiers is to realize power amplification, but the spatial filter is to assure the quality of beam in the near-field, and significant improvements of focusable power in the laser chain also can be achieved[7]. Therefore, it is necessary for the error analysis of the spatial filter in the facility.

Here we fulfill the simulation analysis of one spatial filter (SF1) system in the SG-II facility. The SF1 system is an integration system in the facility and consists of a spatial filter, tube carriage, optical table, and isolation foundation[8]. While the spatial filter structure is fairly simply, and consists of a pair of confocal lens, vacuum tube, and pinhole which position on the focal surface. The isolation foundation is assumed to be rigid. Then we further assume that the optical table is rigid therefore no flexibility of the foundation is included in our analysis. The finite element model of SF1 system can be simplified as shown in Fig. 2. Figure 3 shows that the random acceleration response of the circumstance disturbances originated from the SG-II facility foundation.

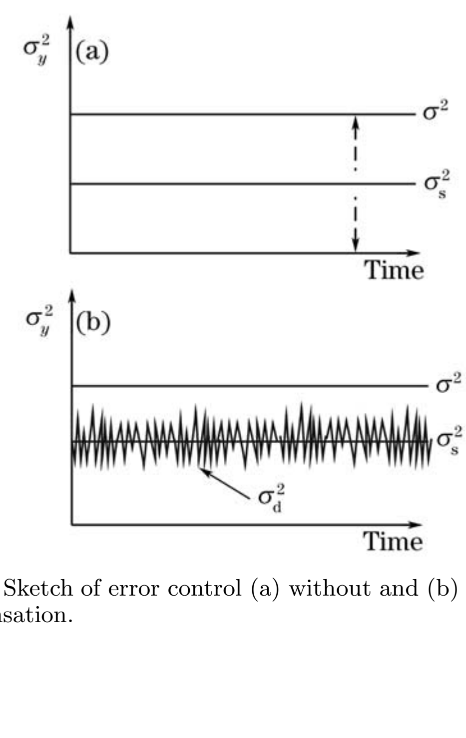

Fig. 1. Sketch of error control (a) without and (b) with error compensation.

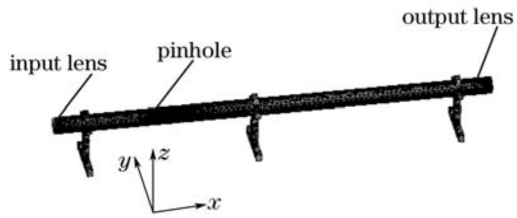

Fig. 2. Finite element model of SF1 system.

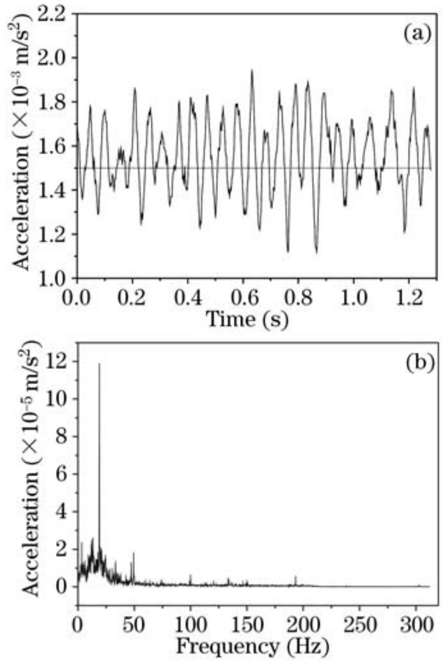

Fig. 3. Acceleration plots for random vibration in SG-II foundation with (a) time domain and (b) frequency domain.

For a spatial filter system, the error related to the target is mainly originated from the displacements of the input lens. So we should more concern on the distortions of the structure of the input lens surface. In the model, the node 163 represents the top surface of the vacuum tube and expresses the maximal displacement of the end of the input lens. In the analysis of the power spectral density (PSD), we choose this node response as the second compensatory analysis.

Figure 4 shows that the displacement spectrum responses of the node 163 excited by random disturbances from the direction z on the base.

From the results, the maximal displacements from the x, y, and z directions are denoted as Δx, Δy, and Δz listed in Table 1. The translation of the beams on the target induced by the translations of the lenses can be expressed as[4]

$$x_{\text{Target due to Lens Motion}} = n \times \Delta x_{\text{Lens}} \times (f_{\text{Target}}/f_{\text{Lens}}), \tag{10}$$

where n is the number of times beam passed by an optical element; Δx_{Lens} is the displacement of lens surface, f_{Target} is the focal length of target and f_{Lens} is the focal length of lens. According to the SG-II facility structure, the values of f_{Target} and f_{Lens} are 750 and 796.76 mm,

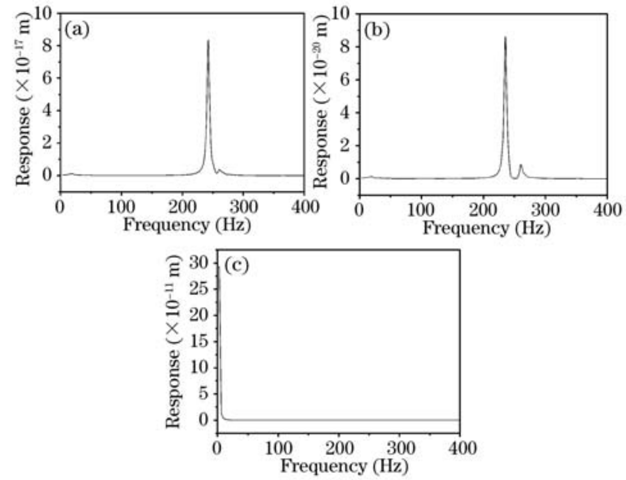

Fig. 4. Displacement spectral responses of the node 163 with (a) x, (b) y, and (c) z directions.

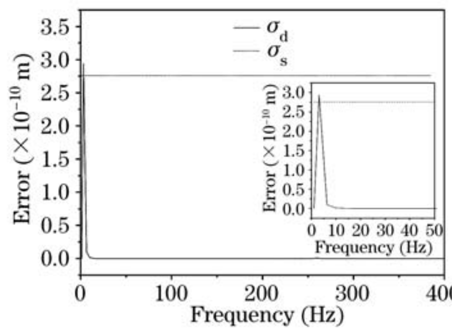

Fig. 5. Error of SF1 system in SG-II facility.

Table 1. Maximum Displacement of the Input Lens Surface

Denomination	Displacement (m)
Δx	0.8355×10^{-16}
Δy	0.8618×10^{-19}
Δz	0.2934×10^{-9}

respectively. The position error of σ_{s} of 0.276×10^{-9} m in the system is obtained.

In the compensatory analysis, the multi-input PSDs are applied on the base of the system shown in Fig. 4 in such as in the directions of x, y, and z, respectively. From the analysis result, the error of SF1 system in SG-II laser facility after compensation is shown in Fig. 5. From it, we can find σ_{d} impacting on the system distinctly even more than the value of σ_{s} in low frequency, and the reason is that the energy of random disturbance mainly exists in low or ultra-low frequency domains. In high frequency, σ_{d} influences on the system very little, and so it is almost neglected.

In conclusion, based on the fundamental error transfer model and the stability requirements of the optomechanical system, firstly, we propose a model of the theoretical derivation and the compensation of the error transfer during a period of time. Then numeral simulation is used to analyze the error of the spatial filter system in the SG-II facility to validate the feasibility of the method. The result shows that the dynamic compensatory error is distinct in low frequency. It also shows that this method can analyze more effectively the beam error induced by the system structure, and provides more reliable basis to estimate the issues of the system stability as well as the dynamic error analysis for the high power laser facility.

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