

Controller Design for Piezo-driven Segmented Fast Steering Mirror

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To improve the performance of laser processing and inter-satellite optical communications, fast steering mirrors (FSMs) for optical path driving are required to have high responsiveness, high accuracy, and large aperture. However, the larger the mirror aperture, the lower the frequency of uncontrollable natural modes and the more difficult it is to increase the bandwidth of the FSM. In this study, an FSM with a large aperture and high response will be realized by integrating small mirror devices (SMDs) with high natural frequencies and wide bandwidth. The SMDs are driven by piezoelectric actuators (PEAs) suitable for high response drives. When multiple mirrors are arranged on the same plane and used as a single mirror, the amplitude of the out-of-plane translational displacement of each SMD increases with the distance between the center of the SMD and the axis of the FSM rotation. Since the relationship between applied voltage and displacement of PEA is nonlinear, the reference frequency responses are affected by the nonlinearities at high frequencies, even with feedback control. Therefore, the integrated mirror surface formed by multiple SMDs will suffer from dynamic flatness degradation. This paper proposes a simple controller gain adjustment based on the similarity of PEA hysteresis to obtain a uniform feedback response of multiple SMDs. The proposed method is experimentally compared with a conventional hysteresis compensation method using the classical Bouc-Wen model. The Bouc-Wen model method requires four tuning parameters, while the proposed method tunes only one. The obtained uniformity of the SMD responses is comparable for both methods, confirming the effectiveness of the proposed method.

NOMENCLATURE

$A_{bw}, B_{bw}, C_{bw}, d_p$ = identified parameters of Bouc-Wen model

h = hysteresis factor

K_{ad_k} = controller gain adjustment factor for M_k

K_I = integral gain of feedback controller

M_k = k -th SMD

M_c = central SMD

V_i = input voltage

V_{max} = maximum voltage for hysteresis identification

w = distance between M_k and M_c centers

z = out-of-plane translational displacement of an FSM

z_{r_k} = reference displacement of M_k in z -direction

z_{out_k} = displacement of M_k in z -direction

α, β, z_0 = identified model parameters of hysteresis used for controller gain adjustment

θ_{ave_n} = average of $\theta_{out_1} \sim \theta_{out_n}$

θ_{out_k} = angle of M_k around the rotation axis

θ_r = reference rotation angle around the rotation axis

θ_x, θ_y = 2-DOF out-of-plane rotation angle of an FSM

σ_n = standard deviation of $\theta_{out_1} \sim \theta_{out_n}$

$\bar{\sigma}_n$ = σ_n divided by the amplitude of θ_{ave_n}

φ = angle between rotation axis and x -axis

1. Introduction

High-performance laser processing and inter-satellite optical communications require a moving mirror called a Fast Steering Mirror (FSM) with a high response, high accuracy, and a large aperture. However, a larger aperture of the FSM lowers the natural frequency of the structure, which is a major obstacle to achieving higher bandwidth.

To achieve a large aperture and high response of FSMs, we have proposed the segmentation of mirrors shown in Fig. 1 [1]. The segmented FSM system with a large aperture and ultra-high response can be realized by integrating small mirror devices (SMDs) with high natural frequency and wide driving bandwidth. The SMDs were developed by combining a tip-tilt driver for 2-DOF out-of-plane rotation (θ_x, θ_y) and a piston driver for out-of-plane translation (z).

However, the hysteresis characteristics of the piezoelectric actuators (PEAs) caused the response to vary with amplitude, even during feedback control. The amplitude dependence of the PEAs response causes variations in the surfaces of the integrated mirrors. Therefore, it is necessary to control the tracking of multiple mirrors by considering the hysteresis characteristics. Hysteresis effects can be reduced by compensation using the hysteresis models. The Bouc-Wen model is popular because it uses relatively few parameters and is highly versatile [2].

In this paper, we proposed a simple controller gain adjustment based on the similarity of hysteresis to reduce the response difference of the SMDs in the z -direction. As a first step, assuming only two SMDs of M_1 and M_2 , as shown in Fig. 1 (b), the standard deviations of their angles with controller gain adjustment were experimentally compared with that of a typical conventional hysteresis compensation method.

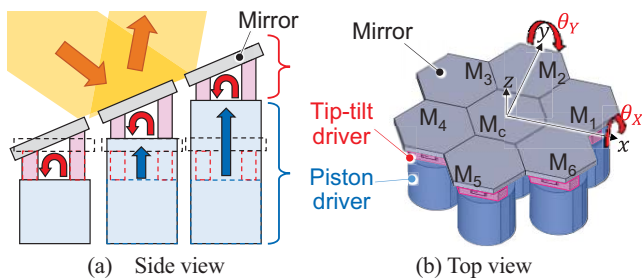


Fig. 1 Concept of a segmented fast steering mirror

2. Experimental Setup

The PEA is continuously driven in experiments with large amplitudes at high frequencies [3]. To prevent damage due to self-heating, the PEA simulating a piston driver for a SMD is cooled using a liquid. Table 1 summarizes the dimensions and performance of the PEA, and Fig. 2 shows a configuration of the experimental setup.

A chiller (LTC-450a, AS ONE) keeps the temperature of the coolant (Novec7300, 3M) to 16–23°C. The PEA under a preload is exposed to the flowing coolant. The preload is adjusted by a screw attached to the plate. The screw end works as the target of a capacitive displacement sensor (console: 5300, probe: 5504, MicroSense). A spherical end plate on the top of the PEA prevents preload distribution.

An FPGA/DSP system (MicroLabBox, dSPACE) is used for digital control. The operating frequency is 100 MHz, and the sampling frequency of the A/D and D/A converters is 1 MHz. The output of the D/A converter is amplified 100 times by a bipolar power amplifier (BP4620, NF).

Table 1 Specification of PEA (AE0707D08H09DF, NEC Tokin)

Dimensions	7.0×7.0×9.0 mm
Free stroke at 150 V	8.7 ± 1.5 μm
Blocking force at 150 V	1700 N
Capacitance	1.4 μF
Operating temperature	-25 to 85°C
Dielectric loss tangent	≤ 5%

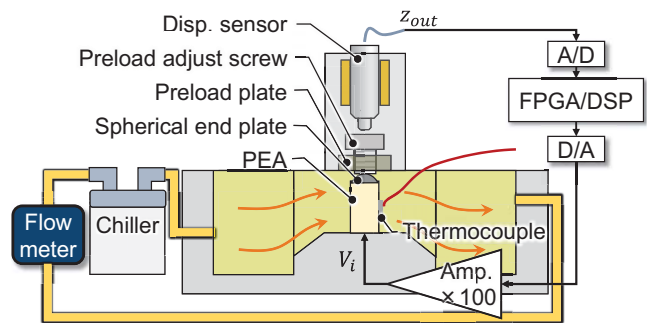


Fig. 2 Configuration of experimental setup as the piston driver

3. Controller Design

3.1 Basic Design of Controllers

The segment FSM consists of a central SMD, M_c , and its surrounding SMDs, $M_1 \sim M_6$, which are controlled to follow the 2-DOF out-of-plane rotation of M_c . As shown in Fig. 3, each SMD is a regular hexagon. In this experiment, assuming no motion error of the tip-tilt drivers, the reference displacements z_{rk} of the piston drivers of M_k are calculated by Eq. (1).

$$z_{rk}(t) = w\theta_r(t) \sin\left((2k-1)\frac{\pi}{6} - \varphi\right) \quad (k = 1, 2, \dots, 6) \quad (1)$$

Where the target rotation angle $\theta_r(t)$ around the axis passing through the center of M_c is sufficiently small. φ is the angle between the rotation axis and the x -axis.

Conversely, the driving z -axis displacements z_{outk} of M_k and the driving angles θ_{outk} around the rotation axis are given by Eq. (2).

$$\theta_{out_k}(t) = \frac{z_{out_k}(t)}{w \sin\left((2k-1)\frac{\pi}{6} - \varphi\right)} \quad (k = 1, 2, \dots, 6) \#(2)$$

This paper compares the three controllers; (1) The case where the same basic feedback controllers are used for the two PEAs. (2) the case where the classical Bouc-Wen model compensation is added to the basic feedback controllers, and (3) the case where simple gain compensation is added to the basic controllers.

Figure 4 shows the overview of the controllers. The basic controller uses an integrator. In this paper, only the tracking control of the piston drivers of M_1 and M_2 is discussed because of the symmetrical arrangement of the SMDs.

3.2 Hysteresis compensator with Bouc-Wen model

The classical Bouc-Wen model is shown in Eqs. (3) and (4) [2].

$$\begin{aligned} z_{out} &= d_p V_i + h \#(3) \\ \dot{h} &= A_{bw} \dot{V}_i + B_{bw} |\dot{V}_i| h + C_{bw} \dot{V}_i |h| \#(4) \end{aligned}$$

Where d_p, A_{bw}, B_{bw} and C_{bw} were identified so that the displacement calculated from Eqs. (3) and (4) fit the measured hysteresis curve of the PEA driven at 1 Hz. h is the hysteresis factor. As shown in Fig. 5, hysteresis compensation is achieved by calculating the hysteresis factor and subtracting the factor from the reference displacement.

3.3 Controller Gain Adjustment

The rise and fall curves are assumed as symmetrical hysteresis, as shown in Eq. (5),

$$z_{out}(t) = \begin{cases} \alpha V_i^\beta(t) + z_0, & \# \dot{V}_i \geq 0 \\ -\alpha(V_{max} - V_i(t))^\beta + \alpha V_{max}^\beta + z_0, & \# \dot{V}_i < 0 \end{cases} \#(5)$$

Considering the similarity of hysteresis of PEAs [2], if the voltage V_i multiplies by X , the displacement z_{out} multiplies by X^β . Thus, z_{out}/V_i becomes $X^{\beta-1}$. Therefore, the controller gain adjustment factor K_{ad} is determined as shown in Eq. (6).

$$K_{ad_k} = \sin^{-1+\frac{1}{\beta}}\left((2k-1)\frac{\pi}{6} - \varphi\right) \quad (k = 1, 2, \dots, 6) \#(6)$$

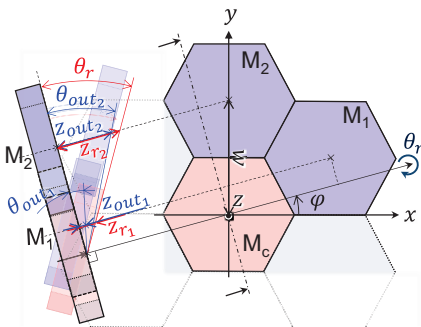


Fig. 3 Axial displacement and tilt angle of each SMD

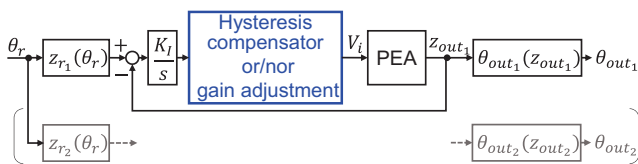


Fig. 4 Basic design of controllers

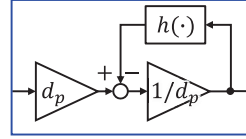


Fig. 5 Hysteresis compensator with Bouc-Wen model

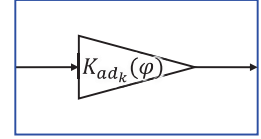


Fig. 6 Controller gain adjustment

4. Experiment

4.1 Evaluation method

The performances of the three types of controllers are evaluated with dimensionless standard deviations $\bar{\sigma}_n(t)$. $\bar{\sigma}_n(t)$ is obtained by dividing the deviation $\sigma_n(t)$, which represents the angle variation of a group of n mirrors, by the amplitude of the average $\theta_{ave_n}(t)$ of the driving angles of the group of mirrors, and non-dimensionalized.

Since only two mirrors are focused on in this paper, $n = 2$, and θ_{ave_n} and σ_n are described by Eqs. (7) and (8).

$$\theta_{ave_2}(t) = \frac{\theta_{out_1}(t) + \theta_{out_2}(t)}{2} \#(7)$$

$$\begin{aligned} \sigma_2(t) &= \sqrt{\frac{1}{2} \sum_{k=1}^2 (\theta_{out_k}(t) - \theta_{ave_2}(t))^2} \\ &= |\theta_{out_1}(t) - \theta_{out_2}(t)| \#(8) \end{aligned}$$

4.2 Controller Parameters

The Bouc-Wen model parameters for the hysteresis compensator are summarized in Table 2. The controller gain adjustment parameters are summarized in Table 3. A comparison between the fitting curves calculated using these parameters and the measurement is shown in Fig. 7. K_I was set to 1000000 /s by trial and error.

4.3 Experimental Result

$\theta_{out_1}(t), \theta_{out_2}(t)$ and $\bar{\sigma}_2(t)$ for each of the three controllers are shown in Figs. 8 to 10. The amplitude of the reference θ_r is 0.05 mrad, and φ is 0°. Since w is 18 mm, the reference displacement amplitude of SMD₁ and SMD₂ are 0.45 μm and 0.90 μm, respectively.

Comparing σ during simple feedback control and feedback control with hysteresis compensation using Bouc-Wen model, the hysteresis compensation reduces both the maximum and RMS for 2 cycles of $\bar{\sigma}_2(t)$. The controller gain adjustment also resulted in smaller maximum and RMS of $\bar{\sigma}_2(t)$ than with simple feedback control. Moreover, they were slightly smaller than the hysteresis compensator. The Bouc-Wen model for the hysteresis compensation requires four tuning parameters, while the proposed controller gain adjustment needs only one. The obtained uniformity of the SMD responses is comparable for both methods, confirming the effectiveness of the controller gain adjustment.

Table 2 Parameters of Bouc-Wen model

d_p	0.0363 $\mu\text{m/V}$
A_{bw}	-0.0208 $\mu\text{m/V}$
B_{bw}	0.155 /V
C_{bw}	0.234 /V

Table 3 Parameters of controller gain adjustment

β	1.27
α	0.00962 $\mu\text{m/V}^\beta$
V_{max}	100 V
z_0	0.105 μm

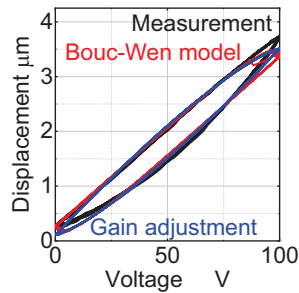


Fig. 7 Hysteresis measurement and the fitting curves

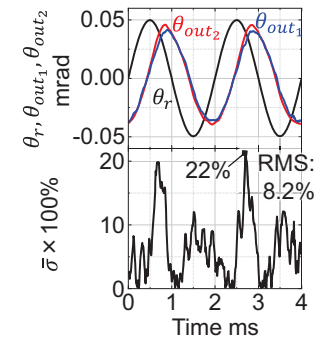


Fig. 8 $\theta_{out1}, \theta_{out2}$ and $\bar{\sigma}_2$ with the simple feedback controller

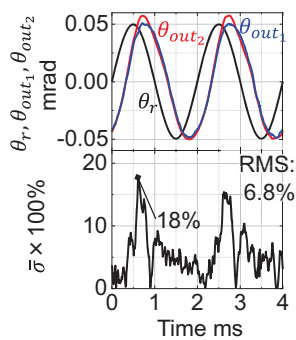


Fig. 9 $\theta_{out1}, \theta_{out2}$ and $\bar{\sigma}_2$ with the feedback controller with hysteresis compensator using Bouc-Wen model

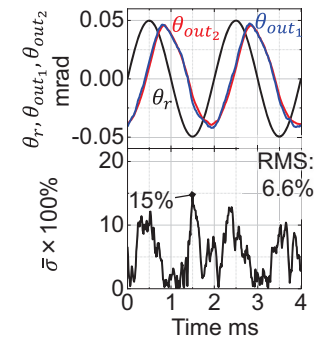


Fig. 10 $\theta_{out1}, \theta_{out2}$ and $\bar{\sigma}_2$ with the simple feedback controller using the proposed gain adjustment

methods for continuously varying the angles of the FSM rotational axis, its rotational amplitude, and frequencies.

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5. Conclusion

To increase the aperture and bandwidth of FSMs, a segmented FSM consisting of multi-piezo-driven SMDs having high natural frequencies is proposed. The reference displacement of the piston drive of each SMD is proportional to the distance between the rotational axis of the integrated FSM and each SMD. Because of differences in the target position of each SMD, variations in the mirror positions during high-frequency drive become significant, requiring compensation with the hysteresis characteristics of the PEA.

Therefore, we focused on the similarity of the PEA hysteresis characteristics and proposed a controller gain compensation method using only one identified parameter. Although the proposed controller gain adjustment method has fewer parameters and is simpler than hysteresis compensation with Bouc-Wen model, it can reduce the standard deviation to the same level as the hysteresis compensation method. Future work will investigate compensation