Bimorph-Type Optical Actuator Using PLZT Elements (Position Control of Optical Actuator by On-Off Control)*

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An optical actuator consisting of PLZT elements is a new type of actuator that makes active use of energy and information of light, and is inherently robust to electromagnetic noise. PLZT is an element that produces mechanical strain by the photostrictive effect when irradiated by ultraviolet light. Since displacement of the element is very small, we adopt a bimorph structure for the optical actuator to increase the displacement. In this paper, we propose an effective position control method for the bimorph-type optical actuator; its validity is confirmed by experiments. A simple on-off control is insufficient to control the optical actuator because the mechanical shutters controlling light irradiation have a large time lag. A new control method, taking into account the dynamic responses of the optical actuator and the shutters, is introduced into the system, and improves the precision and response speed of the optical actuator.

Key Words: Measurement and Control, Actuator, Piezo-Element, Optical Servo System, Optical Actuator, PLZT Element, Position Control, On-Off Control

1. Introduction

Today's servo systems that make full use of electric and electronic technology are used, in general, to improve their performances. On the other hand, the electromagnetic noise environment generated by such devices is growing severe, and it is important to consider the electromagnetic noise problem from standpoints of safety and reliability. Optical servo systems that actively uses energy and information of light not only solve the electromagnetic noise problem, but also have some other advantages such as non-contact supply of energy and so forth. Therefore, realization of the optical servo system is expected,

and fundamental studies of the optical actuator that are indispensable to the optical servo system are in progress⁽¹⁾⁻⁽³⁾.

There are relatively few studies of optical servo systems. Of significance is Hattori's study on trial construction of optical microgrippers and motion characteristics⁽⁴⁾ and Fukuda's study on position control of optical actuator by PWM⁽⁵⁾. Research and development of control methods for the optical servo system are expected to increase in the near future.

An on-off control is best for the bimorph-type optical actuator using PLZT elements, but a simple on-off control suffers from problems in accuracy of control. Thus, in this study we propose an on-off control algorithm that controls the displacement of the optical actuator by predicting the states of the optical actuator and a mechanical shutter which controls the light irradiation based on models of the response characteristics of the optical actuator and dynamic characteristics of the shutter obtained from experiments. Furthermore, we show the on-off control method of validity.

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Fig. 1 Photovoltaic effect of PLZT element

2. Bimorph-Type Optical Actuator

2.1 Structure of optical actuator

In this study the subject of control experiments is the bimorph-type optical actuator using PLZT ceramic elements. The PLZT element is a type of piezoelectric elements, and has electrodes at both ends in polarized direction. Irradiating ultraviolet light with wavelength of 365 nm generates the current in the element by photovoltaic effect as show in Fig. 1. As a result, since the extremely high voltage occurs between the electrodes on both ends of the element, the PLZT element produces mechanical strain by piezoelectric effect. In general, these two effects are called a 'photostrictive effect.' However, since the displacement is very small as few μm , we make the optical actuator which has bimorph structure on experimental basis to get larger displacement to several hundred μm . The trial bimorph-type optical actuator (hereinafter, 'the optical actuator') consists of a pair of PLZT elements that are adhered in an opposing polarized direction by epoxy adhesive, and have common electrodes at the both ends as show in Fig. 2. For example, as shown in Fig. 2, when ultraviolet light irradiates the upper PLZT element, the element stretches in the polarized direction by the photostrictive effect. Although the lower PLZT element is not illuminated by ultraviolet light, since the lower PLZT element has opposite polarized direction and common electrodes with the upper element, the lower element experiences negative voltage and thereby contracts by piezoelectric effect. The net result is that the entire optical actuator bends downward. Illumination of the lower element causes the optical actuator to bend upward.

In general, the chemical composition of PLZT is given as follow :

In this study, PLZT ceramics that have composition of $y=0.03$, $z=0.52$ is used because the best performance of photostrictive effect is expected. Our experimental optical actuator consists of a pair of PLZT

Fig. 2 Structure of bimorph-type optical actuator

elements adhered to each other. The dimensions each element are $W=20\text{ mm}$, $H=20\text{ mm}$, $D=0.5\text{ mm}$. The bimorph has the plate which length is $l=15\text{ mm}$ for measuring displacement at the top end.

2.2 Characteristics of optical actuator

The displacement of the optical actuator, when one side of the optical actuator is illuminated by ultraviolet light of constant intensity L , is the sum of the displacement caused by bending of the PLZT bimorph and the displacement of the plate for measuring displacement caused an angle of deflection at the top of the bimorph. It is expressed as follows :

$$x(t) = d_{33}E(L) \cdot \frac{1.5H}{D} \cdot \left(\frac{H}{2} + l \right) \quad (1)$$

x : Displacement of optical actuator, m

t : Time, sec

d_{33} : Equivalent piezoelectric constant of PLZT element, m/V

E : Photovoltaic field occurred by photovoltaic effect, V/m

L : Intensity of ultraviolet light, W/m^2

H : Distance of electrodes, m

D : Thickness of PLZT element, m

l : Length of plate for measuring displacement, m

A step response of the photovoltaic field $E(L)$, when illuminated by ultraviolet light, is expressed as follows :

$$E(L) = \frac{V_L}{H} (1 - e^{-(t/T)}) \quad (2)$$

$$T = CR \quad (3)$$

V_L : Final photovoltage occurred by step response, V

T : Time constant, sec

C : Electric capacitance of PLZT element, F

R : Electric resistance of PLZT element in state of ultraviolet irradiation with intensity L , Ω

After substituting Eq.(1) into Eq.(2) the displacement with time can be expressed as follows :

$$x(t) = A \cdot V_L (1 - e^{-(t/T)}) \quad (4)$$

$$A = \frac{1.5d_{33}}{D} \cdot \left(\frac{H}{2} + l \right)$$

Fig. 3 Displacement of optical actuator

Here, A is a constant that is decided by a dimension of the optical actuator, and an equivalent piezoelectric constant is $d_{33}=370 \times 10^{-12}$ m/V. This equation shows that it has a characteristic of first order lag. The calculated result for the constant A and the time constant T from the dimension of the PLZT elements that used in this study and the light intensity $L=1$ kW/m², are $A=337 \times 10^{-6}$ and $T=3.39$ respectively. The maximum displacement is 183 μm.

The experimental response of the optical actuator when one side is continuously illuminated by ultraviolet light of intensity $L=1$ kW/m² is shown by a thick line in Fig. 3. According to this experimental result, the maximum displacement is 185 μm, and the time constant is 7.8 sec. In regard to the maximum displacement, the experiment coincides with the calculation. As for the time constant, however the experimental value is 2.3 times larger than the theoretical value. Possible causes are as follows. PLZT ceramics differ because of unwanted non-uniformity in composition. Furthermore, ultraviolet light has the required intensity in the center of the PLZT, but the intensity decreases in the radial direction because of diffusion. Substituting of experimental values into Eq.(4) yields the displacement $x(t)$ for time t :

$$x(t)=185 \times (1 - e^{-(t/7.8)}) \quad (5)$$

In Eq.(5), displacements are given in μm. The calculated result of Eq.(5) is shown by a thin line in Fig. 3. Since the line coincides with the experimental result, it is possible to express the displacement with time when irradiating ultraviolet light by Eq.(5). Henceforth, we use Eq.(5) derived experimentally as an empirical model to express the characteristics of the optical actuator.

The optical actuator possesses property that it maintains displacement fundamentally without ultra-

Fig. 4 Experimental setup of optical actuator system

violet irradiation, after having made some initial displacement induced by irradiation. It cause this phenomenon that the voltage that occurred by photovoltaic effect is fundamentally held while a long time because the common electrodes at the ends are isolated from each other as shown in Fig. 2.

3. Experimental Setup

The outline of the experimental setup is shown in Fig. 4. The light from a mercury xenon lamp inside of the light source is monochromized ultraviolet light of 365 nm wavelength passed through a multiple layer coating optical filter having super narrow band width characteristics. Light is transmitted to the optical actuator via optical fiber. The light intensity is $L=1$ kW/m² on the surface of PLZT elements. Control of the mechanical shutter inside of the light source is done by a computer. In this way, the on-off of the ultraviolet light is controlled. For example, when only the left side of the optical actuator is illuminated by the ultraviolet light, opening the shutter of the left light source while the shutter of the right light source is still closed, the left PLZT element of the bimorph elongates and the right PLZT element contracts. As a result, the optical actuator bends to rightward on the whole. The tip displacement of the optical actuator is measured by a laser-type displacement sensor. According to the result processed the displacement data by a computer, the on or off command is sent to the shutter.

4. Fundamental Control Experiment and its Problem

4.1 Simple on-off control

At first, using the above setup, we make an experiment of the simple on-off control. In this experiment, the control method is that ultraviolet light which increases the displacement illuminates the optical

Fig. 5 Step response (simple on-off control)

actuator when the displacement is smaller than the reference input, ultraviolet light which decreases the displacement illuminates the optical actuator when the displacement is larger than the reference input, and both ultraviolet lights do not illuminate the optical actuator when the displacement is same as the reference input. The result in case of step response which reference input is 50 μm is shown in Fig. 5.

4.2 Problem of current system

For steady state, the displacement of the optical actuator vibrates as shown in Fig. 5. This is a result of sending the off command when the displacement reach the reference input is too late, since the mechanical shutter inside of the light source has a time lag. By moving a shutter plate by an electric solenoid and a spring, the shutter can be made to turn on or turn off the light. As shown in Fig. 4, setting the light intensity meter in place of the optical actuator, the light intensity is measured when some commands which consist of some combination of on and off commands are sent to the shutter. As a result, the following properties become clear. In case that the interval of time between the on command and the next off command for a closed shutter is too short, irradiation does not occur because the shutter does not open sufficiently. When irradiation occurs, there is a time lag of approximately 0.1 sec.

5. Sliding On-Off Control

5.1 Control experiment

To solve the above problem, one needs to control the optical actuator as the velocity become zero when the displacement reaches the reference input, that is, the deviation is zero. Thereafter we define the reference velocity S_r in proportion to the deviation, to make the velocity slower as the displacement

Fig. 6 Step response (sliding on-off control)

approaches the reference input. If there is a deviation, the optical actuator is illuminated by the ultraviolet light which make decrease the deviation. In case of the larger deviation, the ultraviolet light illuminates the optical actuator continuously because the reference velocity S_r is faster than the maximum velocity which is finite value in the real actuator. In case of the smaller deviation, the on and off commands are sent repeatedly, as the real velocity S becomes equal to the reference velocity S_r because the reference velocity is slower than the maximum velocity of the optical actuator. As a result, the velocity vanishes, when the deviation is zero. In this paper, we call this method a 'sliding on-off control.'

We make an experiment of a step response of reference input 50 μm , using the sliding on-off control, and its result is shown in Fig. 6. In this case, the displacement converges to the reference input without vibration, however the velocity slows down gradually past 35 μm .

5.2 Discussion

Since the velocity intentionally slows as the displacement approaches the reference input by the sliding on-off control, response speed is sacrificed against the convergence. The response speed of the present PLZT element is slow as the material characteristic. Therefore, it is important to control precisely using its possible performance without loss of the response speed. It is the best way to send an off command at a certain point near the reference input after continuous irradiation and just stop the displacement at the reference input. Therefore, modeling the response characteristic of the optical actuator and the dynamic characteristic of the shutter inside of the light source, we consider the control method based on the prediction of the motion in the next chapter.

6. Prediction On-Off Control

6.1 Algorithm

To make the strain of the optical actuator at the maximum velocity, and to make it stop on the reference input, the problem is the time lag of the shutter said above. One also must consider the time to close the shutter. Therefore, we consider a method that the on and off command are sent on basis of the prediction of the optical actuator and the shutter that derive from the above characteristics.

At first, measured the displacement, the light source which will be used are selected on basis of the sign of the deviation. In case of no deviation, off commands are sent to both light sources. Therefore, irradiation times T_n and T_l are calculated and compared toward the selected light source. The irradiation time T_n is a time that the optical actuator needs to reach the reference input from the present displacement. And the irradiation time T_l is a time that the ultraviolet light is irradiated until the shutter closes really because of the time lag if an off command is sent at this moment. If T_n is longer than T_l , an on command is sent. But instead if T_n is shorter than T_l , an off command is sent. An off command is sent to another light source at this moment. Repeating the above algorithm every sampling time, the optical actuator is controlled.

The irradiation times T_n and T_l must be calculated. At the outset, we consider the irradiation time T_n that the optical actuator needs to reach the reference input from the present displacement. As above, the displacement of the optical actuator generated by constant intensity ultraviolet light illuminates the optical actuator which original displacement is zero is expressed by Eq. (5). Solving Eq. (5) for time t yields:

$$t = -7.8 \cdot \log\left(1 - \frac{x}{185}\right) \quad (6)$$

This shows the irradiation time that the optical actuator needs to strain from zero to a displacement x using ultraviolet light that intensity is $L=1 \text{ kW/m}^2$. Therefore, it is thought that the irradiation time T_n needed to strain from a certain displacement x_o to the reference displacement x_r is a difference between the irradiation time that it needs to strain from zero to the displacement x_r and the irradiation time that it needs to strain from zero to the displacement x_o . The irradiation time T_n is shown as follows:

$$T_n = 7.8 \cdot \log\left(1 + \frac{x_r - x_o}{185 - x_r}\right) \quad (7)$$

Second, we consider the irradiation time T_l caused the time lag of the shutter when an off command is sent. The shutter plate of the shutter inside of the light source is driven by an electric solenoid and

Fig. 7 Control algorithm

a spring. In state that an input to the shutter is on, the shutter plate is applied constant force by the electric solenoid, and is accelerated constantly until the shutter opens completely. In state that an input to the shutter is off, since the force of the electric solenoid does not act, the shutter plate is accelerated constantly to the opposite ward by the return force of the spring until the shutter closes completely. Considering the area of the optical fiber is enough smaller than the area of the shutter plate of the shutter, it is possible to assume that the on-off state of the irradiation changes immediately when the shutter plate goes through a certain point. Modeling as above and calculating the motion of the shutter plate, the time T_l it takes from sending off command to terminating the irradiation is calculated.

In this paper, we call this control method a 'prediction on-off control.' The algorithm of the prediction on-off control is shown in Fig. 7.

6.2 Control experiment

Using the prediction on-off control algorithm as shown in Fig. 7, we make experiments of the step response and the frequency response. In the experiments of the step response, the reference inputs are $50 \mu\text{m}$ and $70 \mu\text{m}$. In the experiment of the frequency response, the amplitude is $50 \mu\text{m}$, and the frequency is 0.05 Hz . The sampling time is 0.01 sec .

The experimental results of the step response for $50 \mu\text{m}$ and $70 \mu\text{m}$ are shown in Fig. 8 and Fig. 9, respectively. The thin line in Fig. 8 is the result of the sliding on-off control that makes the velocity in proportion to the deviation. Although the displacement converges to the reference input, it takes about

Fig. 8 Comparison of step responses (50 μm) Fig. 9 Comparison of step responses (70 μm)

3.0 sec. On the other hand, the thick line in Fig. 8 is the result of the prediction on-off control that predicts the necessary irradiation time of the ultraviolet light. The displacement reaches the reference input about 2.3 sec without deceleration until the reference input. Its response is improved. The precision is under $\pm 1 \mu\text{m}$ after converging the reference input. In case of 70 μm , it seems to be improved too, and the tendency is more conspicuous.

To discuss the ability of the tracking for the input changed with time, the result of the frequency response experiment in case of the simple on-off control is shown in Fig. 10, and the result in case of the prediction on-off control is shown in Fig. 11. In Fig. 10 and Fig. 11, the thin lines are the reference inputs which amplitudes are 50 μm , and which frequencies are 0.05 Hz, and the thick lines are experimental results. In case of the simple on-off control, the displacement tracks the reference input with vibration

Fig. 10 Frequency response (simple on-off control)

Fig. 11 Frequency response (prediction on-off control)

as shown in Fig. 10. On the other hand, for the case of the prediction on-off control, reducing the vibration the displacement tracks the reference input as shown in Fig. 11, and the control precision is improved. Although the errors of the simple on-off control are more than $\pm 5 \mu\text{m}$ as shown in Fig. 10, the errors of the prediction on-off control are less than $\pm 3 \mu\text{m}$. However, in case of larger amplitudes or higher frequencies, the optical actuator cannot track the reference input sufficiently because the necessary velocity partially over the maximum velocity the optical actuator has.

6.3 Discussion

The PLZT element for the optical actuator induces a current by photovoltaic effect when exposed to ultraviolet light, a voltage difference between the electrodes, and a displacement by piezoelectric effect. The electrical model of the photovoltaic effect of the PLZT element is expressed as a parallel circuit with

constant current source, electric condenser and electric resistance⁽²⁾. The slow response of the optical actuator is attributable to a very small photovoltaic current, when compared to the electric capacity of the element. Although the velocity is slow, the optical actuator moves immediately when illuminated by the ultraviolet light and stops immediately when the irradiation is stopped because the photovoltaic effect responds to the irradiation almost immediately. On the other hand, the response of the shutter inside of the light source is slow, and the shutter cannot be closed immediately. As a result, it is difficult to control in the area that deviation is small. In this study, it is shown that precise control of the displacement of the optical actuator by the prediction of the optical actuator and the shutter is possible without sacrificing the response. It is especially efficacious for the control of a step response.

7. Conclusion

In this study, it is shown that the precise displacement control is possible with relative high response making use of the maximum performance of the optical actuator by modeling the characteristics of the optical actuator and the mechanical shutter inside of the light source.

Hereafter we are going to improve the optical actuator system by using a high response shutter and

a high precision sensor for more precise displacement control and to advance the control method.

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