PLZT Ceramic Driving Rotary Micro-mirror Based on Photoelectric-electrostatic Mechanism

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Abstract: Based on the anomalous photovoltaic effect of PLZT, a rotary micro-mirror driven by hybrid photoelectric-electrostatic actuation of PLZT ceramic is proposed. Firstly, the mathematical modelling of coupled multi-physics fields of PLZT ceramic is established during illumination and light off phases. Then, the relationship between the rotation angle and the photovoltage of PLZT ceramics is established. In addition, the feasibility of rotary micro-mirror with hybrid photoelectric-electrostatic driving is verified via closed-loop control for photo-induced voltage of PLZT ceramic. The experimental results show that the photo-induced voltage of PLZT ceramics has good dynamic control precision using on-off closed-loop control method.

1. Introduction
Driving and control system of micro-mirror based on the micro-opto-electro-mechanical system (MOEMS) technology has the features of small size, light weight, low power consumption and compatible with large scale integrated circuit manufacturing technology. It is widely applied in optical communication, biomedical imaging, optical precision measurement and other military and civil fields. Combined with different micro-mirror driving device, MOEMS micro-mirror can achieve the intensity and phase modulation of the incident light as well as the gating of light path, which contribute micro-mirror to have many functions such as optical switching, scanning and detecting. At present, there are some popular driving modes such as piezoelectric, electromagnetic, and electrostatic driving, etc. [1]. The above-mentioned driving methods have their own advantages and disadvantages so that they can be used in different operating environment and technical fields according to their characteristics. However, all of them need to be driven by an external power. It is not only susceptible to electromagnetic interference, but also has more limitations working in the clean operating space, vacuum environment and other independent working environment. Compared with the above-mentioned driving mode, optical drive technology has the advantages of driving cleaning, such as no electromagnetic interference, non-contact remote optical control and wireless energy transmission, which is an ideal driving mode for MOEMS micro mirror in an independent operating environment [2]. PLZT ceramic can produce anomalous photovoltage effect and photo-induced deformation in the near-ultraviolet band, and can produce the voltage of several kV/cm and displacement of photo-induced deformation in the polarization direction. Therefore, the photovoltage and photo-induced deformation effect of PLZT ceramics can be applied in the driving mode for MOEMS micro-mirror, which can offset the drawbacks of traditional micro-mirror driving mode and have a wide application prospect.
The mathematical model of PLZT ceramic with coupled multi-physics fields is a basis for the theoretical analysis of MOEMS rotary micro-mirror with PLZT ceramics. The mathematical model of PLZT ceramic has been studied by some scholars in recent years. In 1983, RC charging circuit model was proposed to describe the photoelectric field intensity in polarized direction by Brody et al [3], but did not analyze the change of the electric field after the light turned off. In 1993, Fukuda et al [4] experimentally confirmed that the photostrictive effect of PLZT ceramic is the result of multi-physical fields coupling, however, the coupling relationship of different physical fields has not been modeled. In 2005, Shih et al [5] proposed a photostrictive constitutive model of PLZT ceramic; however, they ignored the impacts of thermal expansion on the electric field. Considering the effect of thermal expansion on the photoelectric fields, Wang and Huang et al [6, 7] proposed a mathematical model of photovoltage and photo-induced deformation based on coupled multi-physical fields in 2014. Meanwhile, they experimentally verified the established mathematical model and deduced the light-electric-thermo-mechanical coupling constitutive equation of PLZT ceramic deformation during light off stage. In addition, Zheng et al used the finite element method to construct the constitutive model in 0-1 and 0-3 polarized PLZT ceramic [8]. Jiang et al established an electrical model of hybrid photostrictive/piezoelectric actuation mechanism [9], which provides a theoretical basis for the closed-loop control of PLZT ceramics in micro-driving fields.

Aiming at the shortcomings of traditional MOEMS micro-mirror driving method, a rotary micro-mirror driven by hybrid photoelectric-electrostatic driving of PLZT ceramic is proposed. Firstly, working principle of the rotary micro-mirror mechanism based on hybrid photoelectric-electrostatic driving is present. Then the relationship between the rotary angle and the photo-generated voltage of PLZT ceramic is established. Finally, the feasibility of rotary micro-mirror with hybrid photoelectric-electrostatic driving is verified via experiment of closed-loop control for the photo-generated voltage of PLZT ceramic.

2. Working Principle of the Rotary Micro-mirror with Photoelectric-electrostatic Driving

The rotary mechanism of micro-mirror can make a lot of advantages for micro-mirror such as a large adjustable angle range, the fast response speed and the small volume. A novel rotary micro-mirror with hybrid photoelectric-electrostatic driving based on the anomalous photovoltage effect of PLZT ceramic is shown in figure 1. The micro-mirror is supported by the support column and the flexible support beam. One driving electrode is plated on the non-reflective surface (i.e. lower surface) of the micro-mirror and the other driving electrode is plated on one the upper surface of the base. The driving electrodes are respectively connected to the electrodes of the PLZT ceramic. When the PLZT ceramic is irradiated by the high-energy ultraviolet light, the photovoltage of PLZT ceramic is applied on the driving electrodes of the micro-mirror. Based on the electrostatic driving force between the driving electrodes, the micro-mirror is rotationally driven.

![Figure 1. Rotary micro-mirror with hybrid photoelectric-electrostatic driving](image-url)
As a mature rotary micro-mirror technology which has been widely used in MOEMS micro-mirror, the electrostatic twisting mechanism has lots of advantages, such as simple structure, fast response, no assembly error, small size and easy control [10]. If two rotation mechanisms in two directions are required, the rotary micro-mirror mechanism with hybrid photoelectric-electrostatic driving based on PLZT anomalous photovoltage effect can be respectively arranged in the x and y directions on the moving platform of the micro-mirror translation mechanism. It is also possible to arrange numerous rotating micro-mirror mechanisms proposed in this paper on the moving platform of the micro-mirror to form the array of optical control micro-mirror.

3. Multi–physics Fields Coupling Model of Photo voltage of PLZT Ceramics

Photovoltage can be generated when the PLZT ceramic is irradiated by ultraviolet light. Afterwards, the photo-induced deformation is produced based on the inverse piezoelectric effect. However, the photovoltage of the PLZT ceramic is not proportional to the photo-induced deformation which is far behind the photovoltage. The reason is that the thermal expansion caused by the increase of PLZT ceramic temperature under the UV light cause the hysteresis. Therefore, the photostrictive effect of PLZT ceramic is a comprehensive result of coupled multi-physics field such as anomalous photovoltaic effect, photothermal effect, pyroelectric effect, thermal expansion effect and piezoelectric effect [11]. Figure 2 shows the coupling relationships of multi-physics fields of PLZT ceramic photostrictive effect.

As shown in figure 2, a part of the light energy is converted to thermal energy by the photothermal effect (light energy to thermal energy conversion), which causes the rising temperature. The majority of electric energy is generated in the poling direction based on the anomalous photovoltaic effect (light energy to electric energy conversion) and the pyroelectric effect (thermal energy to electric energy conversion). Another portion of electric energy is produced in opposite direction with the poling direction based on thermal expansion and the direct piezoelectric effect (mechanical energy to electric energy conversion). The total strain includes the thermal expansion strain (thermal energy to mechanical energy conversion) and the piezoelectric strain (total electric energy to mechanical energy conversion).

According to the coupling mechanism analysis of photovoltage effect, the photovoltage expression of PLZT ceramic can be written as [12]:

\[
V(t) = V_p(t) + V_e(t) - \beta V_p(t)
\]

\[
= V_p(1 - e^{-\frac{t}{\tau_p}}) + \left(\frac{AP}{C_p} - \beta \frac{\lambda D}{d_s Y_s} \right) \Delta T_s (1 - e^{-\frac{t}{\tau_s}})
\]

Figure 2. The coupling relationships of multi-physics fields of PLZT ceramic
where $d_{31}$ indicates the piezoelectric constant of the PLZT ceramic; $V_p$ is photovoltage and $V_p(t) = V_{e}(1 - e^{-\frac{t}{\tau_e}})$, where $V_e$ is saturated photovoltage, $\tau_e$ is the illumination time constant; $V_0$ is pyroelectric and $V_0(t) = \frac{AP\Delta T_s}{C_P}(1 - e^{-\frac{t}{\tau_0}})$, where $A$ is the electrode area of PLZT ceramic, $P$ is the pyroelectric coefficient of PLZT ceramic [13], $\Delta T_s$ is the maximal temperature variation, $\tau_0$ is the thermal time constant; $\lambda$ is the thermal stress coefficient of PLZT ceramic; $Y_a$ is the elastic modulus of PLZT ceramic; $V_e$ is Thermal deformation voltage and $V_e(t) = \frac{\lambda D_e}{d_3} \Delta T_s (1 - e^{-\frac{t}{\tau_e}})$, where $D_e$ is the distance between the two electrodes of PLZT ceramic and $\beta$ is the conversion coefficient of thermal deformation and electric field.

After UV light is switched off, the residual voltage and deformation of PLZT ceramics gradually decrease to the initial state of the PLZT before illuminated. Investigating the trend of PLZT ceramics in the light-off phase can help further study of photo-deformation characteristics of PLZT ceramics and promote the engineering application of PLZT ceramics. The residual voltage after turning off the UV light can be obtained as:

$$V_d(t) = V(t_0) + V_{p-d}(t) - \beta V_{e-d}(t)$$

$$= V(t_0) - \left(\frac{AP}{C_p} - \frac{\beta_2 \lambda D_e}{d_3 Y_a}\right) \Delta T_{s-d} + \left(\frac{AP}{C_p} - \frac{\beta_2 \lambda D_e}{d_3 Y_a}\right) \Delta T_{s-d} e^{-\frac{t}{\tau_d}}$$

where $\Delta T_{s-d}$ is the maximal temperature decrement during light-off phase and $\Delta T_{s-d} = T(t_0) - T_0$; $T(t_0)$ is the temperature of PLZT ceramic when the ultraviolet light is switched off; $\tau_d$ is the dark time constant. $\beta_2$ is the conversion coefficient of thermal deformation and electric field during light switched off.

4. Rotation Angle of the Micro-mirror with Hybrid Photoelectric-electrostatic Driving

As shown in figure 3, it is a cross-sectional schematic view of the rotary micro-mirror mechanism with hybrid photoelectric-electrostatic driving, where $h_m$ is the vertical distance between the flexible support beam and the driving electrode on the base; $l_m$, $w_m$ and $t_m$ are the length, width and thickness of the flexible support beam respectively; $a_m$ is the width of the micro-mirror. Thus, with respect to the rotary axis, the position of the driving electrode on the base (i.e., $s_1$ and $s_2$) should satisfies the relation of $s_1 = a_1 a_m$, $s_2 = \alpha_2 a_m$.

![Figure 3. Cross profile of rotary micro-mirror with hybrid photoelectric-electrostatic driving](image)

When the PLZT ceramic is irradiated by the UV light, a photo-induced voltage of several kV/cm is generated and applied to the driving electrodes of the micro-mirror via the lead wire. Micro-mirror will be rotationally driven due to electrostatic force, therefore, the electrostatic moment $M_e$ is obtained as [14]:

$$M_e = \frac{1}{2} \pi \mu_0 \varepsilon_0 \epsilon_0 V^2 \frac{a_m}{l_m}$$
Finally, the voltage

\[ M_v = \int_{\alpha a_m}^{\alpha a_m} F dx = \int_{\alpha a_m}^{\alpha a_m} -\frac{e L_m V^2}{2(h_m - x \tan \theta_m)^2} dx \]

\[ = \frac{e L_m V^2}{2\theta_m^2} \left[ 1 + \frac{1}{1 - (\alpha_s a_m / h_m)\theta_m} + \frac{1}{1 - (\alpha_s a_m / h_m)\theta_m} + \frac{1}{1 - (\alpha_s a_m / h_m)\theta_m} \right] \]  

where \( e \) is the conductivity of air.

In order to simplify the electrostatic moment expression of the rotary micro-mirror, suppose

\[ \Theta = \theta_m / \theta_{m-max} \], where \( \theta_{m-max} \) is the maximum twist angle of the rotary micro-mirror, \( \theta_{m-max} = h_m / a_m \)
is obtained from the geometric relationship, the electrostatic moment \( M_e \) can be simplified as [14]:

\[ M_e = \frac{e L_m V^2}{2\theta_m^2} \left[ 1 - \frac{1}{1 - \alpha_s \Theta} + \frac{1}{1 - \alpha_t \Theta} \right] \]  

According to the theory of torsional deformation in the mechanics of materials [15], when the micro-mirror is rotated under the action of electrostatic force, the recovery torque produced by the flexible support beam is:

\[ M_r = S_0 \theta_m \]  

where \( S_0 \) is the torsional stiffness of the flexible support beam and \( S_0 = 2Gl_p / l_m \), where \( G \) is the shear elastic modulus of support beam.

The torsional cross-section modulus of the flexible support beam of the micro-mirror is [16]:

\[ I_p = t_m w_m^3 \left[ \frac{1}{3} - 0.21 \frac{w_m}{t_m} (1 - \frac{w_m}{t_m}) \right] \]  

where \( w_m \leq t_m \).

According to the principle of moment balance in material mechanics, it can be obtained that

\[ M_e = M_r \]. So the relationship between the PLZT ceramic photovoltage and the rotation angle of the micro-mirror can be written as:

\[ V = k_0 \sqrt \frac{1}{\left\{ \frac{1}{1/(1 - \alpha_s \Theta)} - [1/(1 - \alpha_t \Theta)] \right\} + \ln([1/(1 - \alpha_s \Theta)]/[1/(1 - \alpha_t \Theta)])} \]  

where \( k_0 = \sqrt \frac{S_0 \theta_m^{2-max}}{e L_m} \).

5. Close-loop Control for Photovoltage of PLZT Ceramic

5.1. Experimental Setup of Close-loop Control for Photovoltage of PLZT Ceramic

In this section, the feasibility of rotary micro-mirror with hybrid photoelectric-electrostatic driving is verified via closed-loop control for photo-induced voltage of PLZT ceramic. By using the light shutter to control the UV light on and off, the dynamic closed-loop control of photovoltaic voltage can be achieved.

Experimental setup of closed-loop control for photovoltage of PLZT ceramic is illustrated in figure 4. Firstly, start the software of the servo control system written by LabVIEW in the computer. Afterwards, enter the target value of voltage and initialize the light shutter to "ON". When the UV light is switched on, PLZT ceramic produces photovoltage, which is measured by a high impedance voltmeter and the data is acquired and processed by servo control program. Afterwards, the voltage data are transferred to the optical shutter control thread. Then via serial port, the control command is inputted to the light shutter. Finally, closed-loop servo control for photovoltage of PLZT ceramic is achieved.

Since the closed-loop control scheme is carried out based on the photovoltage of PLZT...
ceramic is real-time measured and feedback, so test program for the high impedance voltmeter is written and developed using LabVIEW.

(1) UV light controller, (2) High impedance voltmeter, (3) Probe of high impedance voltmeter, (4) Controller of optical shutter, (5) UV probe, (6) Optical shutter, (7) PLZT ceramic, (8) Computer

**Figure 4.** Experimental setup of close-loop control for photovoltage of PLZT ceramic

5.2. Experimental Results of Closed-loop Control of PLZT Ceramic Photovoltage

The closed-loop photovoltage control experiment of single PLZT ceramic is carried out, where the sampling period is set to 300 ms and the target voltage is set to 1000V. Figure 5 shows the experimental curve of the closed-loop photovoltage control of single PLZT ceramic with light intensity of 50mW/cm$^2$ and 100mW/cm$^2$. As illustrated in figure 5(a), the photovoltage of PLZT ceramic takes about 18.3s to increase to the target value when the light intensity is 50mW/cm$^2$. Afterwards, the photovoltage fluctuates around the target voltage, and the average fluctuation height average wave height $f_1$ is 23V. As shown in figure 5(b), the PLZT ceramic photovoltage takes about 8.1s to reach the target voltage when the light intensity is 100mW/cm$^2$ UV light. The average fluctuation height $f_1$ is 54V.

![Experimental results](image)

(a) Light intensity is 50mW/cm$^2$ (b) Light intensity is 100mW/cm$^2$

**Figure 5.** The closed-loop photovoltage control curve of single PLZT ceramic

The experimental results verify the feasibility of hybrid photoelectric-electrostatic driving micro-mirror. Because of the limitation of the sampling frequency of the high impedance voltmeter, voltage data is acquired with certain time delay. Improving the sampling frequency of the high impedance voltmeter and the control algorithm will be carried out to achieve a better control effect in our future research.
6. Conclusions

The rotary micro-mirror with hybrid photoelectric-electrostatic driving is proposed based on anomalous photovoltaic effect in PLZT ceramics exposed to high-energy ultraviolet light. The photovoltage equations in illumination phase and light-off phase are obtained. Based on the multi-physics coupling model of PLZT ceramics, the relationship between the rotation angle of the rotary micro-mirror and the photovoltage of the PLZT ceramic is given and analysed. In addition, the closed-loop experimental study on the photovoltage of PLZT ceramics under different light intensities is carried out.

The experimental results show that the time of the photovoltage of PLZT ceramic reaching the target value of 1000V under the illumination of 50mW/cm² and 100mW/cm² is 18.3s and 8.1s respectively. That means the time of PLZT ceramic photovoltage reaches the target value decreases with the increase of light intensity. In other words, the response speed of the closed-loop control system can be improved with stronger UV light. In addition, the fluctuation amplitude of the photovoltage around the target voltage increases gradually when the light intensity increases. The larger fluctuation amplitude of the photovoltage will impact the control accuracy for the micro-mirror. Therefore, our next work is to eliminate fluctuation using variable light intensity control or improving the sampling frequency of the high impedance voltmeter.

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