Micro-mirror with hybrid photoelectric-electrostatic driving of PLZT ceramic

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Abstract. A novel micro-mirror driven by hybrid photoelectric-electrostatic actuation of PLZT ceramic is proposed based on the anomalous photovoltaic effect of PLZT ceramic. On the basis of analysis of coupling relationships of multi-physics fields of PLZT ceramic, the photovoltage of PLZT ceramic is established during illumination and light off phases. Furthermore, the relationship between the driving displacement and the photovoltage of PLZT ceramics is present. In addition, the feasibility of micro-mirror with hybrid photoelectric-electrostatic driving is verified via closed-loop control for photovoltage of PLZT ceramic. The experimental results show that the photovoltage of PLZT ceramics has good dynamic control precision using on-off closed-loop control method.

1. Introduction

Micro-Opto-Electro-Mechanical System (MOEMS) micro-mirror is widely applied in optical precision measurement and communication, biomedical imaging and other military and civil fields because of the merits of small size, light weight, low power consumption, etc. There are some driving methods used most for micro-mirror, such as piezoelectric, electromagnetic, and electrostatic driving, etc. [1]. The above-mentioned driving methods can be used in different operating environment and technical fields according to their own advantages and disadvantages. However, additional external power should be supplied for above-mentioned driving methods. It not only produces 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 driving 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 [2]. Actuation using PLZT ceramic is one of optical driving methods. When illuminated by UV light, PLZT ceramic can produce the voltage of several kV/cm and photo-induced deformation in the polarization direction based on anomalous photovoltaic effect and photostrictive effect. Therefore, the photovoltage and photo-induced deformation of PLZT ceramics can be applied in the driving mode for MOEMS micro-mirror, which can offset the drawbacks of traditional micro-mirror driving method.

The mathematical model of PLZT ceramic with coupled multi-physics fields is a basis for the theoretical analysis of MOEMS micro-mirror with PLZT ceramics. Up to now, the mathematical model of PLZT ceramic has been studied by some scholars in recent years. In 1983, RC charging circuit model was proposed 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, the impacts of thermal expansion on the electric field are ignored in the photostrictive constitutive model. 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. Furthermore, they experimentally verified the established mathematical model. Additionally, Zheng et al [8] established an electrical model of hybrid photostrictive/piezoelectric actuation mechanism. The publications mentioned above provide a theoretical basis for active control for micro-driving with PLZT ceramic.

In this paper, a micro-mirror driven by hybrid photoelectric-electrostatic driving of PLZT ceramic is proposed. Working principle of the micro-mirror based on hybrid photoelectric-electrostatic driving mechanism is present. The relationship between the driving displacement of micro-mirror and the photovoltage of PLZT ceramic is established. The feasibility of micro-mirror driven by hybrid photoelectric-electrostatic mechanism is experimentally verified.

2. Working principle of the micro-mirror with photoelectric-electrostatic driving

A novel 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 located at the free end of the flexible cantilever beam. One copper foil laminated on the lower surface of the beam, the other copper foil is correspondingly fixed on the base. The two copper foils are respectively connected to the electrodes of the PLZT ceramic. When the PLZT ceramic is irradiated by the high-energy ultraviolet light, the photovoltage produced by PLZT ceramic is applied on the two copper foils. Based on the electrostatic driving force between the two copper foils, the flexible cantilever beam will produce a deflection at the free end. Finally, the micro-mirror is driven down.

Since the electrostatic twisting mechanism has lots of advantages, such as simple structure, fast response, no assembly error, small size and easy control [10], which has been widely used in MOEMS micro-mirror.

3. Multi-physics fields coupling model of photovoltage of PLZT ceramics

When the PLZT ceramic is illuminated by UV light, photo-induced voltage is generated in the poling direction based on the anomalous photovoltaic effect (light energy to electric energy conversion); 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. Meanwhile, the rising temperature triggers the pyroelectric effect (thermal energy to electric energy conversion) and thermal expansion effect. Based on thermal expansion and the direct piezoelectric effect, some electric energy is generated (mechanical energy to electric energy conversion). It is noted that the electric field
generated by the anomalous photovoltaic effect and pyroelectric effect are in the same direction as the residual polarization and enhance the internal electric field in PLZT ceramic. However, a portion of electric field produced by the thermal dilatation deformation is in opposite direction with the poling direction and weakens the electric field in PLZT ceramic [11]. Figure 2 shows the coupling relationships of multi-physics fields of PLZT ceramic illuminated by the UV light.

\begin{equation}
V(t) = V_p(t) + V_s(t) - \beta V_e(t)
\end{equation}

where \(d_{3i}\) indicates the piezoelectric constant of the PLZT ceramic; \(V_p\) is photovoltage and \(V_p(t) = V_s(1 - e^{-\frac{t}{\tau_1}})\); \(V_s\) is the saturated photovoltage; \(\tau_1\) is the illumination time constant; \(V_\theta\) is pyroelectric during light on stage and \(V_\theta(t) = AP\Delta T_S/C_p(1 - e^{-\frac{t}{\tau_1}})\); \(A\) is the electrode area of PLZT ceramic; \(P\) is the pyroelectric coefficient of PLZT ceramic; \(\Delta T_S\) is the maximal temperature variation, \(\tau_\theta\) is the thermal time constant; \(\lambda\) is the thermal stress coefficient of PLZT ceramic; \(V_e\) is voltage caused by thermal deformation during light on stage and \(V_e(t) = \lambda D_e/(d_{3i}Y_a)\Delta T_s(1 - e^{-\frac{t}{\tau_1}})\); \(Y_a\) is the elastic modulus of PLZT ceramic; \(D_e\) 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:

\begin{equation}
V_e(t) = V(t_0) + V_{\theta,d}(t) - \beta_2 V_{t-d}(t)
\end{equation}

where \(V_{\theta,d}\) is pyroelectric during light off stage and \(V_{\theta,d}(t) = -\left(\frac{AP}{C_p} - \frac{\beta_2\lambda D_e}{d_{3i}Y_a}\right)\Delta T_{t-d}\); \(\Delta T_{t-d}\) is the maximal temperature decrement during light-off phase and \(\Delta T_{t-d}=T(t_0) - T_0\); \(T(t_0)\) 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 off stage. $V_{e-d}$ is voltage caused by thermal deformation during light off stage.

4. Driving displacement of the micro-mirror with hybrid photoelectric-electrostatic driving

As shown in figure 3, it is a deflection analysis of flexible beam with hybrid photoelectric-electrostatic driving. $l$ is the length of the flexible beam; $b$ is the width of the flexible beam; $d$ is the initial distance between the two cooper foil; $l_{cu}$ and $b_{cu}$ is the length and width of the cooper foil respectively, and $b_{cu}=b$. According to figure 1, the driving displacement of the micro-mirror in Y direction is approximately equal to the deflection of the free tail of the flexible beam.

![Figure 3. Deflection analysis of flexible beam with hybrid photoelectric-electrostatic driving](image)

When the PLZT ceramic is irradiated by the UV light, the photovoltage is generated and applied to the two copper foils via the lead wire. Micro-mirror will be driven due to electrostatic force between the two copper foils. Herein, taking an infinitesimal unit $dx$ along the X direction in the two copper foils is analysed. It is assumed that the two infinitesimal units in the upper and lower copper foil are parallel. Hence, the two infinitesimal units can be taken as a parallel plate capacitor. The formula of capacitance energy $W$ can be written as

$$W = \frac{1}{2}CU^2$$  \hspace{1cm} (3)

where $C$ is the capacitance of the capacitor; $U$ is the potential difference between the two plates of the capacitor.

According to the principle of virtual work, the electrostatic force between the two plates of the capacitor can be defined as

$$dF = \frac{\partial W}{\partial (dw)} = \frac{1}{2} \varepsilon_a b_{cu} U^2 \frac{1}{(d-dw)^2} dx$$  \hspace{1cm} (4)

where $\varepsilon_a$ is the dielectric constant of the air; $dw$ is the deflection of the beam at the location of the infinitesimal unit $dx$.

It is noted that the electrostatic force $dF$ is a concentrated force and located in the region of $[l-l_{cu}, l]$ in X direction. So the deflection of the free tail of the flexible beam $dw_{tail}$ caused by $dF$ can be expressed as

$$dw_{tail} = \frac{dFx^2}{6EI} \hspace{1cm} (l-l_{cu} \leq x \leq l)$$  \hspace{1cm} (5)

Substituting equation (4) into equation (5), one can get the following formula

$$dw_{tail} = \frac{1}{2} \varepsilon_a b_{cu} U^2 \frac{x^2}{(d-dw)^2} \frac{1}{6EI} \hspace{1cm} (l-l_{cu} \leq x \leq l)$$  \hspace{1cm} (6)

According to the working principle of the micro-mirror with photoelectric-electrostatic driving, the photovoltage generated by PLZT ceramic is applied to the two copper foils. Thus, the potential
difference $U$ between the two plates of the capacitor should be replaced by the photovoltage $V(t)$ and $V_d(t)$ expressed in equations (1) and (2). Integrating with respect to $x$, the relationship between the driving displacement ($w_{tail}$) and the photovoltage of PLZT ceramics is established.

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 micro-mirror with hybrid photoelectric-electrostatic driving is verified via close-loop control for photo-induced voltage of PLZT ceramic. The block diagram of close-loop control for photovoltage of PLZT ceramic is shown in figure 4. When the UV light is applied to PLZT ceramic through optical shutter, the photovoltage generated by PLZT ceramic is measured by a high impedance voltmeter and the data is acquired and processed by signal processing module. Afterwards, the voltage data are transferred to the optical shutter control thread. Then the control command is inputted to the optical shutter. Finally, closed-loop servo control for photovoltage of PLZT ceramic is achieved. Experimental setup of closed-loop control for photovoltage of PLZT ceramic is illustrated in figure 5. In the actual operation, the software of the servo control system written by LabVIEW should be started firstly. Afterwards, enter the target value of voltage and initialize the light shutter to "ON".

![Figure 4. Block diagram of close-loop control for photovoltage of PLZT ceramic](image)

![Figure 5. Experimental setup of close-loop control for photovoltage of PLZT ceramic](image)

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. Figure 6 is the program front panel, which is divided into two threads: data acquisition thread and light shutter control thread.
5.2. Experimental results of closed-loop control of PLZT ceramic photovoltage

The closed-loop photovoltage control experiment of single PLZT ceramic carried out, where the sampling period is set to 300ms. Figure 7 shows the experimental curve of the closed-loop photovoltage control of single PLZT ceramic with light intensity of 50mW/cm² and 100mW/cm². As illustrated in figure 7(a), the target value of photovoltage is 500V and 1000V. The photovoltage of PLZT ceramic quickly increases to the target value and then fluctuates around the target voltage. As shown in figure 7(b), the target value of photovoltage is 500V, 800V, 1000V, 1100V and 1300V. The photovoltage of PLZT can successfully keep around the multi-target voltage respectively.

![Voltage graph](image)

**Figure 7.** 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, the photovoltage 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 micro-mirror with hybrid photoelectric-electrostatic driving is proposed based on anomalous photovoltaic effect in PLZT ceramics exposed to UV 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 driving displacement of the micro-mirror and the photovoltage of the PLZT ceramic is established. 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 photovoltage can be successfully controlled around the target value, which means that the deflection of the flexible beam or the driving displacement of micro-mirror can achieve the target value via controlling the photovoltage of PLZT ceramic. Thus, the feasibility of hybrid photoelectric-electrostatic driving micro-mirror is proved.

References
[1] Lu A J, Zhang Z P, Huang Z J2016Optics and Precision Engineering24400-406.
[2] Zhu Y, Liu W, Jia K, et al. 2011Sensors and Actuators A: Physical167495-501.
[3] Brody P S. 1983Ferroelectrics5027-32.
[4] Fukuda T, Hattori S, Arai F, Matsuura H, Hiramatsu T, Ikeda Y and Maekawa A1993Proceeding of IEEE Robotics and Automation Conference 618-23.
[5] Shih H R, Tzou H S and Saypuri M 2005Journal of Sound and Vibration284361-378.
[6] Huang J H, Wang X J and Wang J 2015Smart Materials and Structures 25025002.
[7] Huang J H, Wang X J and Wang J2015Optics and Precision Engineering23760-768.
[8] Zheng S J, Tong LY and Luo Q T2015International Journal of Applied Electromagnetics and Mechanics49513-530.
[9] Jiang J, Li X N, Yue H H and Deng Z Q2017Journal of Mechanical Engineering5365-71.
[10] Huang J M, Liu A Q, Deng Z L, Zhang Q X, Ahna J and Asundid 2004Sensors and Actuators A: Physical115159-167.
[11] Wang X J, Lu F, Liu Y F and Huang J H2016Optics and Precision Engineering242505-14.
[12] Fridkin V M1979Photoferroelectrics (New York: Springer).
[13] Zhong W L1996Ferroelectric physics (Beijing: Science Press)487-488.