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Eliminating hysteresis of piezoelectric deformable mirror by charge control

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ABSTRACT

Inherent hysteresis of piezoelectric deformable mirror (DM) limits the performance of adaptive optics (AO) systems including bandwidth and residual wavefront error. A charge control method based on switched capacitor charge pump was proposed to eliminate the hysteresis of piezoelectric DM. Experimental results show that the hysteresis of a unimorph DM was reduced from 11% to less than 1%. It indicates that the proposed charge control method has the potential to improve the deformation precision for one step correction as well as the bandwidth of the AO systems.

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1. Introduction

Since piezoelectric actuators can generate large force and have high response speed, piezo-driven deformable mirrors (DM) are widely used as wavefront correctors for adaptive optics (AO) applications [1], such as telescope [2,3], optical communication [4], laser beam correction [5], and ophthalmoscope [6]. So far, many kinds of piezoelectric DMs have been developed and can be classified as bimorph/unimorph DMs [7–10] and point-actuated continuous face-sheet piezoelectric DMs [11–14]. As a common feature of the piezoelectric DMs, the inherent hysteresis of piezoelectric material results in a nonlinear relationship between the applied voltage and the mirror deformation on the order of 10%. Hysteresis reduces the performance of the AO system including the bandwidth and the residual wavefront error.

In order to overcome the issue of hysteresis, some mathematical hysteresis models, such as Coleman–Hodgdon model [15,16] and Preisach model [17], have been employed to describe the behavior of piezoelectric DMs. The inversions of these models are used for linearization of the mirror response. Dubra et al. [17] shown that the DM control errors with hysteresis correction were reduced from 20% to around 3% in an open-loop AO system with a Shack–Hartmann wavefront sensor (WFS). Yang et al. [15] demonstrated by simulation that the bandwidth of the AO system was increased 25%–45% under different loop gains after DM hysteresis was corrected. However, these models suffer from the disadvantages of algorithm complexity, parameter uncertainty and heavy computation, limiting their practical applications.

An alternative method is to control piezoelectric actuators by using charge (current) instead of voltage. Electrically, a piezoelectric actuator behaves as a nonlinear capacitor, with the principal nonlinearity being hysteresis in the charge–voltage characteristic. This electrical nonlinearity results from the same dielectric hysteresis as the electromechanical nonlinearity. In theory, the relationship between the mechanical displacement of a piezoelectric actuator and the applied charge is linear [18,19]. In this paper, charge control method is introduced to overcome the hysteresis of piezoelectric DM. To the best of our knowledge, it is the first experimental demonstration of controlling a DM by charge control method.

2. Adaptive optics system

The schematic of the experimental AO system based on charge control is shown in Fig. 1. A collimated He–Ne laser beam passes through the beam splitter (BS), and then is reflected by the DM and directed to the inverted telescopic system. Finally the wavefront of the laser beam is measured by a Shack–Hartman wavefront sensor (WFS, Thorlabs WFS150-5C). A lenslet array of 27×27 is used for measurement. In comparison to traditional high voltage amplify array (HVA), a charge drive array is used to control the

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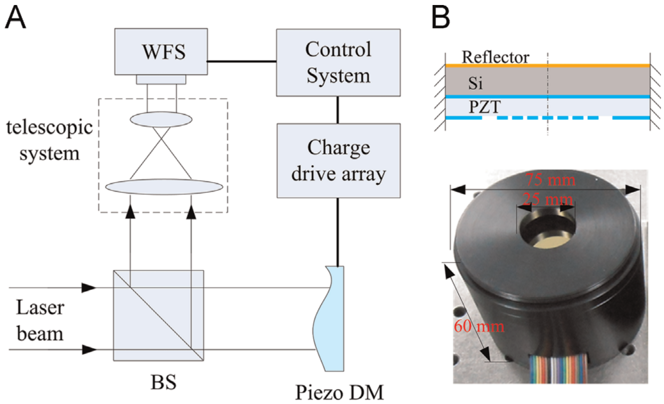

Fig. 1. Experimental setup. (A) Schematic of the experimental AO system with a WFS. (B) Structural illustration and photograph of unimorph DM.

deformation of the DM. In this system, a homemade unimorph DM is used [9], as shown in Fig. 1(B). It consists of a 300 μm thick silicon film and a 100 μm thick PZT film with clamped boundary. The effective pupil of the DM is 15 mm in diameter. The DM has a 37 actuators array with hexagonal arrangement and an outer ring actuator. The actuators array is used to correct aberrations, while the outer ring actuator is used to generate defocus deformation.

3. Charge control

3.1. Control algorithm

Similar to voltage control, the DM mirror can be controlled by charge. The relationship between charge and mirror deformation is

$$\phi = MQ, \tag{1}$$

where ϕ is the mirror deformation (or wavefront) which is usually expressed by a Zernike polynomial coefficient vector or a slope vector of SHWS. Q is a vector of the electric charge applied on the actuators. M is the influence function matrix that describes the relationship between the quantity of charge and the responding deformation of the mirror surface.

The control methods developed based on voltage can be used for charge control directly [20,21]. Since hysteresis is eliminated, the DM can be controlled to correct the measured wavefront in one step rather than iterations, which effectively increases the bandwidth of the AO system. To obtain the charge vector that is required to produce a particular deformation, Eq. (1) is rearranged as:

$$Q = M^{-1}\phi, \tag{2}$$

where the pseudo-inverse M^{-1} can be calculated using the singular value decomposition (SVD).

3.2. Principle of charge drive circuit

Several charge drive circuits have been developed to reduce the hysteresis of the piezoelectric actuator [22–24]. In this work, the charge drive circuit based on switched capacitor charge pump [24] was utilized to control the piezoelectric DMs due to its digitization control and less hysteresis over a large frequency range.

The schematics of one channel switched capacitor charge pump and the process of charge control are shown in Fig. 2. It works as follows: (1) Switch 1 (S1) is connected to the reference voltage source $+E$ or $-E$ which is used for positive or negative charge, respectively. (2) Switch 2 (S2) is connected to the reference voltage, with the other end connecting to the reference capacitor C_f. The capacitor C_f is then charged by electrostatic charge Q_c with the quantity of $+EC_f$ or $-EC_f$. The polarity of charge is controlled by S1. (3) The capacitor C_f is disconnected from the reference voltage and connected to the inverting input of the amplifier. The charge Q_c on the reference capacitor C_f is pumped to the piezoelectric actuator rapidly. The charge increment (can be called as charge packet) on the actuator ΔQ_{act} is equal to Q_c. As above, the process of pumping charge is controlled by switches under the control of microcontroller. Since the directions of deflections are only controlled by S1, the S1 maintains the connection to $+E$ or $-E$ during one step aberration correction. The steps (2) and (3) are repeated n times to reach the aim deformation according to the measurement, as shown in Fig. 2(B). Finally, the total charge on the actuator is:

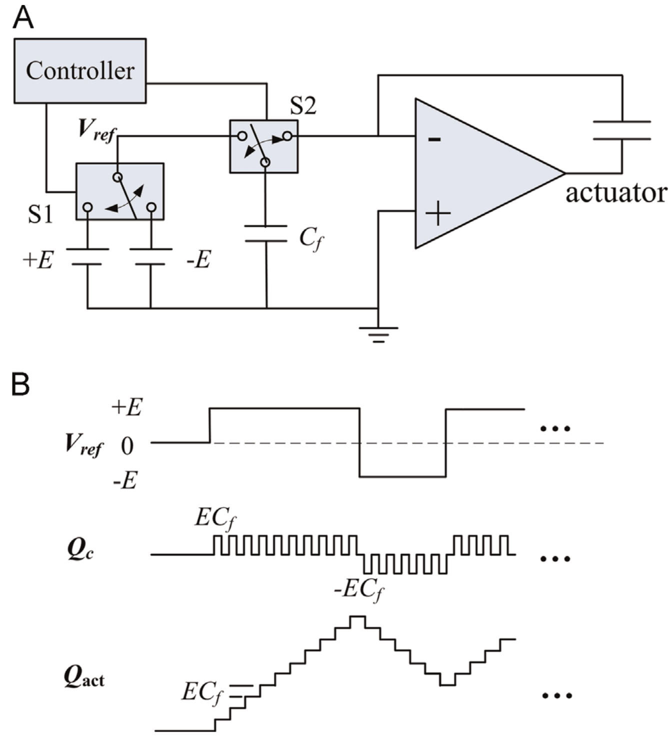

Fig. 2. Principle of charge control method. (A) Schematic of one channel charge drive circuit based on switched capacitor charge pump. (B) Process of charge control.

$$Q_{\rm act} = \Delta Q_{\rm act} + \Delta Q_{\rm act} + \cdots + \Delta Q_{\rm act} = +nEC_f \quad \text{or} \quad -nEC_f \tag{3}$$

In the circuit, the equivalent minimum voltage increment ΔV_{act} is determined by the charge packet $\Delta Q_{\rm act}$, which is expressed as:

$$\Delta V_{\rm act} = \frac{\Delta Q_{\rm act}}{C_{act}} = \frac{C_f}{C_{act}}E \tag{4}$$

where C_{act} is the equivalent capacitance of the actuator. The voltage increment on actuator is related to the reference voltage and the ratio of the reference capacitor and the piezoelectric actuator. In order to improve the deformation resolution, small capacitor and reference voltage can be selected. But this increases the step counts since the charge number in each charge packet decreases. If $C_f = C_{act}/100$ and $E = 5$ V, the increment of the actuating voltage ΔV_{act} is 50 mV. The resolution relative to the voltage range (50 V) is only one in a thousand.

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