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Single piezoelectric ceramic stack actuator based fast steering mirror with fixed rotation axis and large excursion angle

Gang Yuan [a,b,*], Dai Hua Wang [a,b], Shi Dong Li [b]

[a] Key Laboratory of Optoelectronic Technology and Systems of the Ministry of Education of China, Chongqing 400044, China
[b] Precision and Intelligence Laboratory, College of Optoelectronic Engineering, Chongqing University, Chongqing 400044, China

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ABSTRACT

To meet the development demands of the stare imaging system, a single piezoelectric ceramic actuator (PCSA) based fast steering mirror (FSM) with fixed rotation axis and large excursion angle is proposed and designed. The statics model and dynamical model of the FSM are established and analyzed. On this basis, a parameter optimization method is proposed and applied to determine the configuration parameters of the designed FSM. The working principle, excursion angle, and natural frequency of the FSM are validated through theoretical estimating, finite element analyzing by ANSYS, and experimental testing, respectively. The experimental results show that the developed FSM can provide a mechanical excursion angle larger than 3° with natural frequency of 180.4 Hz, and the mechanical excursion angle and the natural frequency can be estimated by the established mathematical models accurately.

1. Introduction

Fast Steering Mirror (FSM, aka tilt mirror) is an adaptive optical mechanism that directs an optical beam between a source and a receiver rapidly and accurately using a reflective surface [15,11]. It has been widely used in the fields of stare imaging system [16], adaptive optics compensation [1,2], acquisition, tracking, and pointing systems [3,4], image stabilization [5], fast laser scanning [6], space optical communication [7], and precision laser beams steering [8,9]. In the application of stare imaging system, the FSM provides a back scan operation against the continuously scanning of the gimbal platform where the afocal optical assembly and the FSM are mounted [16]. To extend the area coverage and improve the resolution of the imagery, there is a strong demand of FSMs with larger excursion angle, smaller dimension, and fixed rotation axis.

In the last two decades, various FSMs have been developed. According to the driving principle, there are two kinds of FSM [3]: the voice coil actuator (VCA) based FSMs and the piezoelectric ceramic stack actuator (PCSA) based FSMs. Compared with the VCA based FSMs, the PCSA based ones, which take the advantages of the small scale, fast response, high resolution in the nano-radian range, rapid dynamic performance, and without electromagnetic radiation, are ideal for dynamic operation (e.g., tracking, scanning, and drift and vibration cancellation) as well as static positioning [17], and have attracted more and more attentions. Janssen et al. [2] designed a cryogenic tip–tilt mirror with tilt range of ±0.3° and the first natural frequency of 355 Hz using piezoelectric actuator. Park et al. [6] designed a piezoelectric-driven tilt mirror with tilt range of 0.04° at 4 kHz. However, due to the small displacement of the PCSA, which is smaller than 2‰ of its length (generally only 30 μm at the maximum) for a PCSA with length of 30 mm, these PCSA based FSMs can only generate excursion angle smaller than 1° in general [10]. Moreover, the rotation axes of these FSM are below the surface of the mirror, even without fixed axes, which raise critical challenge for the design of high-resolution stare imaging system.

In order to realize a PCSA based FSM with large excursion angle, a feasible idea is amplifying the displacement of the PCSA utilizing a bridge-type amplifier [12,13] based on flexure hinges. However, most of the current researches on the bridge-type amplifier are based on the finite element analysis (FEA) method without an accurate mathematical model, which cannot satisfy the requirement of the design and optimization of the FSM. Furthermore, no proper configuration to guarantee a fixed rotation axis on the surface of the mirror can be found for FSM in papers and commercial products.

In this paper, a single PCSA based FSM utilizing a bridge-type amplifier and flexure hinges is proposed and explored. The statics model and dynamical model of the FSM are established, and the characteristics are analyzed. On this basis, the proper structure

* Corresponding author at: Key Laboratory of Optoelectronic Technology and Systems of the Ministry of Education of China, Chongqing 400044, China.
E-mail addresses: cquyuan@cqu.edu.cn (G. Yuan), dhwang@cqu.edu.cn (D.H. Wang), lsdalxn19890424@163.com (S.D. Li).

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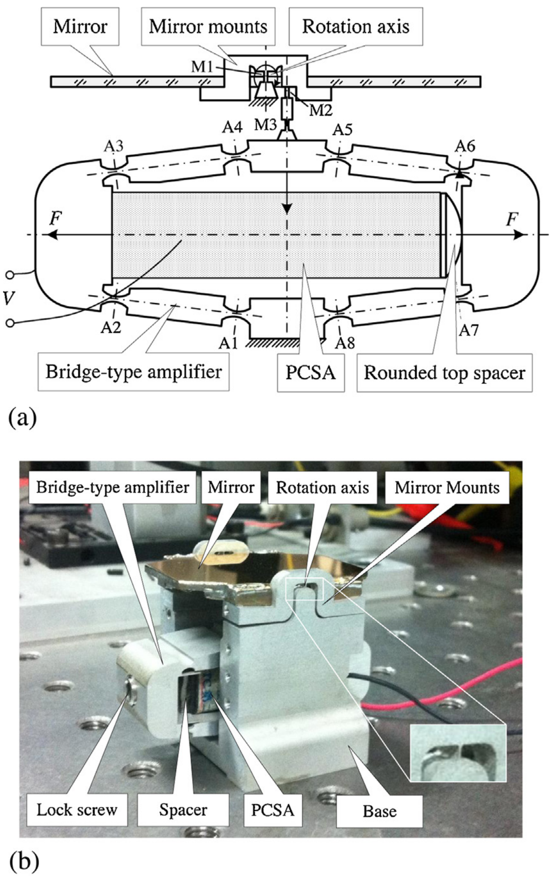

Fig. 1. The single PCSA based FSM with fixed rotation axis and large excursion angle: (a) the configuration and (b) the photograph.

and characteristic parameters of the developed FSM are defined through parameter optimization. Finally, the experimental results of the developed FSM are compared with those estimated according to the established models and simulated by ANSYS.

2. Design and working principle

The key requirements of the single PCSA based FSM are having an operating mechanical excursion angle of 3° and keeping the rotation axis fixed on the surface of the mirror, while maintaining the natural frequency higher than 150 Hz. In addition, the dimension should be smaller than $60 \times 60 \times 50\,\text{mm}^3$ (Length × Width × Height), and the mirror should be larger than $30 \times 20\,\text{mm}^2$.

To meet all the requirements, a FSM with novel configuration is designed and developed. The configuration and photograph of the developed FSM are shown in Fig. 1(a) and 1(b), respectively.

Observing Fig. 1(a), the FSM consists of a mirror, mirror mounts, a set of rods connected by the flexible joints M1, M2, and M3, a bridge-type amplifier, a PCSA, and a rounded top spacer. The mirror and the mirror mounts act as the rod between the flexible joints M1 and M2, where the bottom of M1 is fixed with the base. The bridge-type amplifier consists of eight flexible joints A1, A2, . . ., A8, and six beams between the hinges with the bottom of the amplifier fixed with the base. The PCSA is fixed in the bridge-type amplifier with the rounded top spacer under a proper preload. To simplify the design and analysis, the stiffness of the flexible joints M1, M2, and M3 is the same, and the stiffness of the flexible joints A1, A2, . . ., A8 is the same.

According to Fig. 1(a), the two ends of the bridge-type amplifier translate to the opposite sides under the forces F generated by the

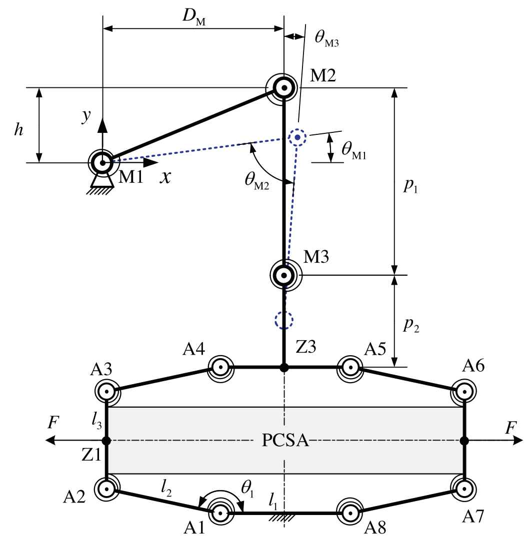

Fig. 2. Pseudo-rigid-body model of the single PCSA based FSM with fixed rotation axis and large excursion angle, where the included angle between the mirror and the base can be defined by θ_{M1}.

PCSA with driving voltage, and the top of the amplifier move down combined with the deformation of the hinges A1, A2, . . ., A8. Then the rods are pulled down and the mirror tilts clockwise around M1. Whereas, the top of the amplifier moves up and pushes the rods up with decreasing the driving voltage. The mirror tilts anticlockwise around M1 under the elastic action of the flexure hinges.

Observing Fig. 1(b), the developed single PCSA based FSM consists of a mirror, a base, a bridge-type amplifier, a PCSA, and a rounded top spacer. The first three are made of aluminum alloy. The flexible joints and the mirror mounts on the base are obtained by wire–electrode cutting. The mirror mounts is connected to the bridge-type amplifier by the rods obtained by wire–electrode cutting. The bridge-type amplifier is fixed on the base by screws, and the mirror is connected with the mirror mounts by screws. The mirror manufactured by precision grinding is plated with gold to increase its reflectivity. In order to reduce the maximum stress at the rotation axis as the FSM operates, the bridge-type amplifier is pre-pressed during the assembling and released properly after the mirror is fixed. In this case, the mirror and the mirror mounts tilt around the rotation axis about half of the maximum excursion angle in the opposite direction, and the maximum deformation angle at the flexible joint M1 relative to the natural state will reduce to about half of the maximum excursion angle during the tilting as well.

3. Mathematical models

To determine the proper structure and characteristic parameters of the FSM, such as the length of the rods, the stiffness of the flexible joints, and the included angle at the bridge-type amplifier, the statics model and dynamical model of the FSM should be established.

3.1. Statics model

Fig. 2 shows the established pseudo-rigid-body model of the proposed single PCSA based FSM as shown in Fig. 1. Observing Fig. 2, the ideal hinges collocated with the tensional springs are equivalent to the flexible joints A1, A2, . . ., A8, M1, M2, and M3, respectively. The rigid linkages are equivalent to the rods and beams between the flexible joints with the bottoms of M1 and linkage A1A8 are fixed. In the initial state, the tensional springs are uncompressed, and the linkages M2M3 and M3Z3 are in line.