Design and performance test of a two-axis fast steering mirror driven by piezoelectric actuators*

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A novel design of a two-axis fast steering mirror (FSM) with piezoelectric actuators is proposed for incoherent laser beam combination. The mechanical performance of the FSM is tested. The results show that the tilting range of the mirror is about 4 mrad, and the 1st-order resonance frequency is about 250 Hz. A self-designed grating encoder is taken as the sensor, which ensures the optimal precision of 10 μrad. The novel mechanical design can meet the requirement of engineering in incoherent laser beam combination.

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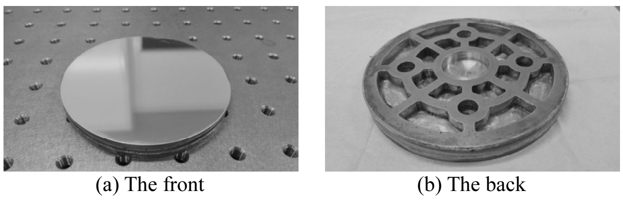
Fast steering mirror (FSM) is a significant component of many optoelectronic systems, such as optical communication, image stabilization, adaptive optics compensation and fast laser scanning[1-6]. Therefore, FSM is always a research focus for recent decades. Comparing with doing research on mechanical design of FSM, more researchers prefer to controller design and system identification with mature products of PI Company (Germany), Newport Corporation (American) and Optics in Motion (Canada)[7]. However, the mechanical self-design technology of FSM system not only helps to meet the special need of engineering and save the cost, but also has important directive to nanometer positioning and machining. At present, most mechanical designs of FSM are mainly based on voice coil actuator (VCA), and few researchers prefer to the mechanical design of FSM based on piezoelectric actuators (PZA)[8,9]. The former is more popular in application of large angle scanner, while the latter is more popular in application of wide bandwidth. For the sake of restraining the aberration caused by strong turbulence, a wide bandwidth FSM is necessary in incoherent laser beam combination system. In this paper, a novel mechanical design of a two-axis FSM based on PZA is introduced.

FSM mechanical system consists of the actuators, the supports, the sensors, the mirror, the base and the house. The size of the mirror is decided according to the desire of optical design, but it affects the mechanical performance a lot. Generally, small size mirror can lead to high density of laser power, which can cause thermal distortion of mirror surface. On the other side, it is hard to improve the bandwidth of the system with a large size and heavy mirror. Therefore, for a suitable size of mirror, it is important to choose a light-weight but high-strength material as the base of mirror and adopt the light-weight technology if necessary. In order to completely receive the laser beam with a diameter of 60 mm and an incident angle of 45°, the diameter of mirror is set to 90 mm. Aerial aluminum alloy (7A04) is taken as the base of the mirror for its advantages of relative light weight, low cost and good heat dissipation. The sector open light-weight structure helps to cut down the inertia of the mirror as shown in Fig.1. The thickness of the mirror is 9 mm, and the width and thickness of the ribs are 4 mm and 5 mm, respectively. The analysis of the mirror distortion with finite element analysis (FEA) method shows that the root mean square (*RMS*) distortion of mirror surface is less than 1/40 of the green wavelength under the inertia moment at the frequency of 100 Hz.



(a) The front (b) The back

Fig.1 The aluminum alloy mirror

VCA and PZA are two main actuators for FSM system[10]. Contrast to VCA, PZA exhibits faster response,

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higher resolution and larger driving force[11]. So PZA becomes more popular in FSM system for high bandwidth applications. However, PZA has short stroke which is about 0.1% of its size, so it is often utilized with magnifying mechanism. Rhomboid or elliptical magnifying mechanism has been reported twice to be used in laser scanner[12,13]. Compared with the multi-lever structure with spring preload, it is more compact and easy to set preload by adjusting the thickness of the pad. Fig.2 shows the assembly of the rhomboid mechanism proposed in this paper and PZA from PI Company (P-887.91, Germany). Considering a tradeoff between magnification and stiffness in output direction, the angle between the arm of rhomboid and the PZA is set to 10°, and the width of the arm is set to 1.2 mm. A test on magnification of the rhomboid mechanism with experimental setup shown in Fig.3 proves that it can amplify the stroke of PZA by 3.5 times. The stiffness in output direction is about 1.2 N/μm, and the stiffness in the direction of PZA being placed is about 18 N/μm according to FEA method. The preload is set to 180 N by grinding the pad to the certain thickness which is 10 μm more than the gap between rhomboid and PZA.

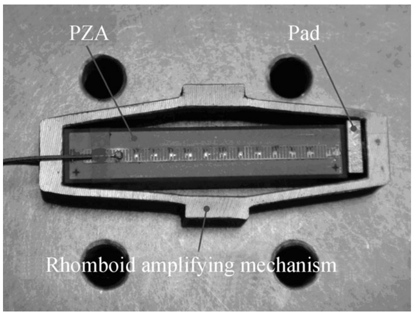


Fig.2 The assembly of the rhomboid amplifying mechanism with PZA

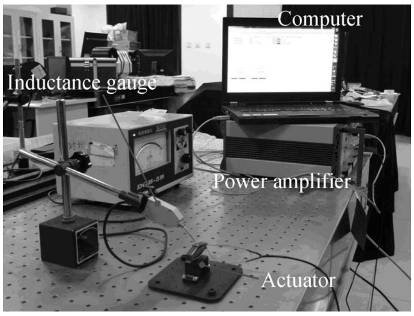


Fig.3 The experimental setup for testing the magnification of the rhomboid mechanism

A famous two-axis support for the FSM based on VCA was reported in Ref.[14]. However, it is not suitable for the one based on PZA, because there is an extension of PZA from the state of power cut to the state of ready to work, and it leads to high stress in center support which has been explained in detail in previous work[15]. An excellent flexure support is the around support of PI products which requires a strict processing. A novel around flexure support as shown in Fig.4 is taken in the proposed FSM system. The support consists of one flexure ring and four flexure bars. The flexure bars can effectively transmit the driving force and absorb the tangential displacement when the mirror tilts for protecting PZA from shear force. The flexure ring can restrain the degree of freedom (DOF) in non-working direction, and raise the resonance frequency of the system. The analysis with FEA method shows that the 1st-order resonance frequency is more than 300 Hz when ignoring the inertia of PZA, and the high order resonance frequency is over 2 000 Hz.

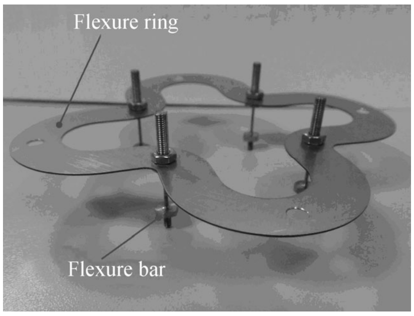


Fig.4 The flexure support of the FSM

Four self-designed linear absolute grating encoders as shown in Fig.5 are taken as the sensors of FSM[16]. The probes of the encoders are distributed evenly on a circle with diameter of 94 mm. There are two actuators and two encoders on each axis, so that it can be seen as a single input and single output (SISO) system when ignoring the influence of the coupling. Therefore, it is easy for controller design. The encoders have fast response and a measuring range of 5 mm with the precision of 1 μm, so the optimal precision of the FSM is 10 μrad.

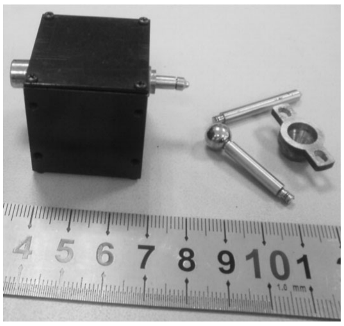


Fig.5 The self-designed grating encoder

The whole structure and outside view of the FSM are shown in Figs.6 and 7. Besides the elements mentioned above, there is also a base with high stiffness and a house for dustproof.

Experiments were carried out to test the mechanical performance of the FSM. Fig.8 shows the schematic diagram of experimental setup. The DSP28335 receives the feedback information from encoders, and then sends out the order to drive the PZA with high voltage source from PI Company (E-500, Germany).

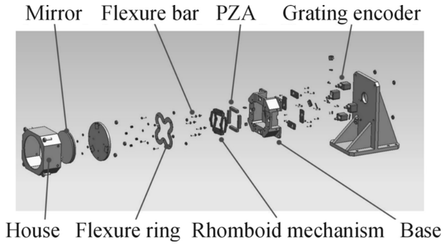


Fig.6 The explosive view of the FSM

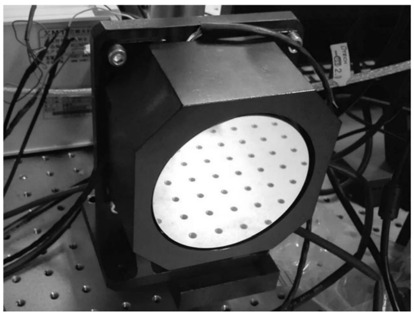
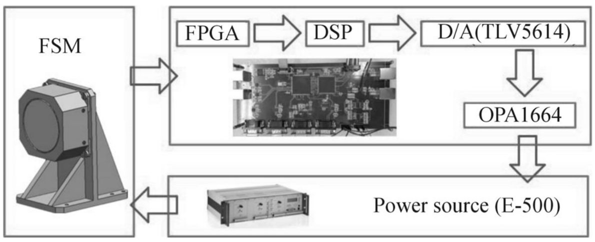


Fig.7 The outside view of the FSM



FPGA: field programmable gate array; DSP: digital signal processor; D/A: digital-to-analog converter; OPA: optical parametric amplifier

Fig.8 The experimental setup for testing mechanical performance of the FSM

Firstly, the tilting range of the FSM system was tested with different frequencies. As shown in Fig.9, the tilting range is about 5 mrad under the frequency of 1 Hz and is about 4 mrad under 80 Hz. The hysteresis phenomenon cannot be observed clearly because it is compensated with a feed forward controller named as rate-independent Prandtl-Ishlinskii model[17,18].

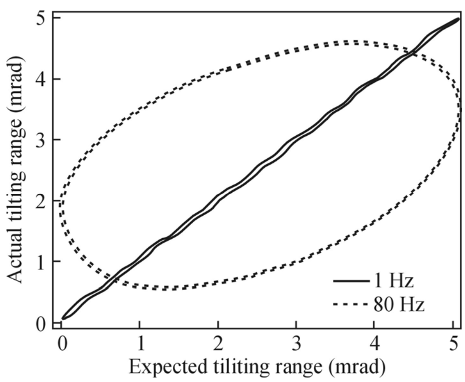
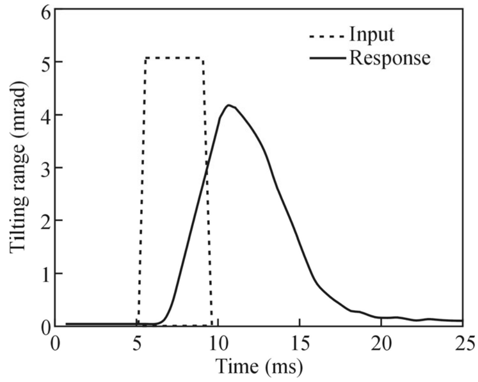
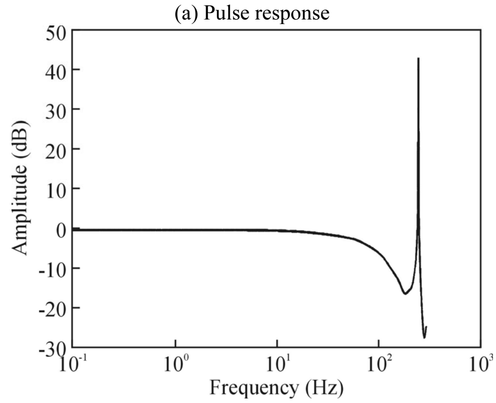


Fig.9 The tilting range of the FSM with different frequencies

A pulse response test was carried out for dynamic properties of the FSM system, and the results show that the 1st-order resonance frequency is about 250 Hz as shown in Fig.10.



(a) Pulse response



(b) The Bode diagram of transfer function

Fig.10 The system identification with the pulse response

In summary, a novel mechanical design of FSM system is proposed in this paper. The design of each element is introduced. The FSM system which has the mirror with diameter of 90 mm, tilting range of 4 mrad and the 1st-order resonance frequency 250 Hz can meet the requirement of the engineering in incoherent laser beam combination system. A sector open light-weight structure is taken to cut down the inertia and raise the resonance frequency in FSM system. A novel flexure support for FSM based on PZA is proposed to protect PZA and raise the resonance frequency, and it is easy to be processed. The compact, self-designed linear absolute grating encoders are taken as the sensor, which can be an attempt to substitute the gauge sensor.

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