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Development of ultra-small fast steering mirror for spectroscopic sensor with high speed and excellent disturbance rejection characteristics

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Fast steering mirror has been applied in the field of optics and chemical analysis because it can compensate the tilting error when the moving mirror assembly moves for optical translation in spectroscopic sensors. The important factors in removing the tilting error quickly and effectively in Michelson type interferometer are how to design, manufacture and develop the fast steering mirror. It is also essential to verify that it can satisfy the design requirements for the actual spectroscopic interferometer application by evaluating the design parameters and performances, including the stiffness and disturbance rejection characteristics, etc. In this paper, we present the ultra-small fast steering mirror with the leaf spring mechanism which can reduce the effect of the external disturbance. We proposed the new mechanical structure including the piezoelectric actuator and elastic guide to satisfy the design requirements such as steering angle, steering speed, spring stiffness, and robustness of disturbance to apply the proposed device on a portable spectrometer. By testing the performance after fabrication, it is verified that the proposed ultra-small fast steering mirror is capable of steering motion with its angle of several milliradians and speed of hundreds of Hz. Also, the optical testing result in the laboratory scale test-bed bed shows that the proposed fast steering mirror can compensate the tilting error within 10 arcseconds and can be applied to the actual spectroscopic interferometer in future.

1. Introduction

The spectroscopic sensor for gas monitoring at a distance is composed of so many precise optical units including a Michelson interferometer, in which the light of a single wavelength is divided by the optical beam splitter and the transformation of these two divided lights is executed. Inside the interferometer unit, light path difference between these two divided beams which are reflected by a fixed and a moving mirror respectively, is very important for precise detection of various several gases (1). In most cases, it is generated by precision electromagnetic actuators which can produce a linear repeated motion of several millimeter and nearly flat motion profile. However, the optical path generated by these actuators can be distorted due to the product assembly and other environmental errors which can occur in the mechanical actuation unit guided by bearing components. Therefore, by introducing a fast steering mirror that can compensate for the distortion of the optical axis at high speed, it is possible to prevent the performance degradation of the interferometer unit and secure the ease of alignment in the actual spectral sensor product. Also, fast steering mirror with tilting error compensation capability should be made as small as possible so that the user can handle the portable spectroscopic sensor easily (2).

In this study, an ultra-small fast steering mirror for a portable spectroscopic sensor for long-distance gas monitoring was designed and fabricated, and a performance test was conducted. A fast steering mirror that can satisfy the required specifications of the spectroscopic sensor was manufactured using three piezoelectric actuators and elastic hinge. By finite element method, these specifications were reviewed in advance whether the proposed fast steering mirror can meet the required specifications or not, for example, the steering angle, frequencies, and resolution, etc. Also, the performance of the proposed fast steering mirror has been verified in the optical test bench. Especially, the mechanical structure with higher resonance frequency, were proposed and tested for the high speed and better disturbance rejection characteristics.

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2. Design and testing of ultra-small fast steering mirror

2.1 Design and manufacture

Fig. 1(a) shows the fast steering mirror that has been designed for the particular application of real-time compensation of tilting errors considered in this investigation. The FSM holds a flat fused silica mirror with diameter of 20 mm bonded on a mirror adapter guided with flexible rings. For better disturbance rejection, several dimensions of flexible ring and mirror were determined to implement the higher resonant frequency characteristics by finite element analysis as shown in Fig. 2(a) and (b). The mirror is tilted in θ_X, and θ_Y directions by three stacked type piezoelectric actuators of very small rectangular cross-sections, whose dimensions are 5x5x16mm. A strain gage type displacement sensor with high resolution is installed within the FSM to measure the longitudinal motion of the piezoelectric actuator, which is subsequently closed-loop controlled to compensate for the non-linear positioning characteristic of the piezoelectric actuator due to hysteresis. The full operating range of the FSM is 0.1 degree with a fast dynamic response of 100 Hz cut-off frequency bandwidth. As shown in Fig. 1(b), a prototype of fast steering mirror was manufactured with a size of 18x31mm, diameter × length. It was built with titanium alloy (Grade 5) and the flexible ring was manufactured by wire EDM.

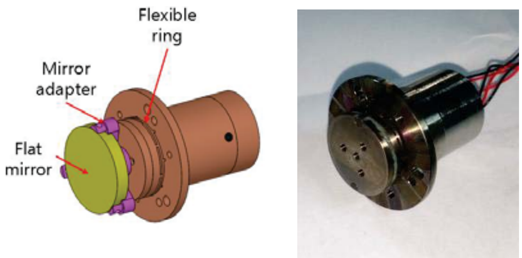

Fig. 1 Fast steering mirror to correct tilting error: (a) solid (b) photograph of the manufactured fast steering mirror

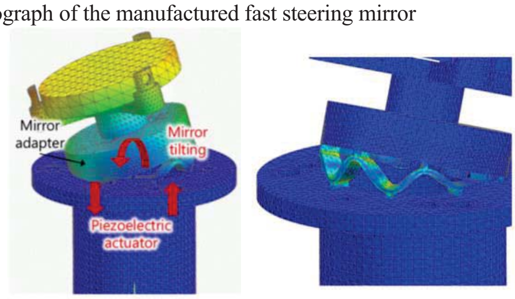

Fig. 2 Finite element analysis to examine FSM motion: (a) mirror tilting due to the piezoelectric actuators; (b) Von Mises stress contour plot (279MPa)

2.2 Testing

To evaluate the performance, an experimental setup was constructed as shown in Fig. 3(a). The purpose of the experiment is to determine the steering angle, resolution, and bandwidth of the proposed fast steering mirror. The measurement setup consists of a laser source, a fast steering mirror that reflects the beam irradiated from the laser source and a two-axis optical sensor (Position Sensing Detector Mount, PSDM) that measures the position of the beam spot on the rectangular sensing area of 10×10 mm. When the proposed fast steering mirror is driven in two directions, horizontal (θ_X) and vertical (θ_Y) directions, a two-axis optical sensor can detect the laser beam spots that are generated in the X and Y directions, as shown in Fig. 3(a). As shown in Fig. 3(b), The frequency response function was measured by applying a sine sweep signal from 0 to 700 Hz to the piezoelectric actuator using a dynamic signal analyzer. It was found that resonant frequency of fast steering mirror was 658 Hz. In addition, to measure the resolution, input voltage was applied to the piezoelectric actuator in a stepwise fashion. The response of fast steering mirror was measured using PSDM. It can be found that the manufactured fast steering mirror has a minimum resolution of about 0.4 arcsec. Also, the output steering angles were measured when the sinusoidal input signal is input to drive the piezoelectric actuators.

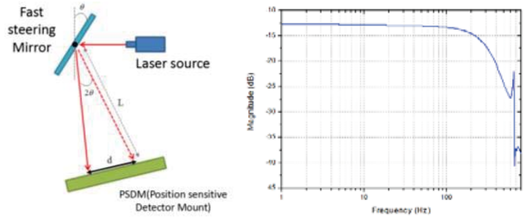

Fig. 3 Optical test bench with FSM for performance evaluation: (a) schematic; (b) frequency response function

3. Conclusions

An ultra-small fast steering mirror for a portable spectroscopic sensor was designed and fabricated to compensate the tilting error. Through finite element method, several design parameters were reviewed in advance. Also, an optical test bench was built for the testing of the fast steering mirror and its performance was evaluated. In future, the experiment to compensate for the distortion of the optical path caused by the moving mirror is to be performed to confirm its disturbance rejection capability of the proposed fast steering mirror.

Table 1 Major performances of proposed fast steering mirror

Items	Result
Size	18x31mm, D×L
Steering angle	0.1 degree
Steering resolution	0.4 arcsec
Resonance frequency	658 Hz

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