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Development of flexure-based moving reflector with voice coil motor for the optical gas imaging

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Abstract

The moving reflector is a key component of the multi-species gas detection in the optical gas imaging device which can serve a repetitive high-speed moving function in the spectroscopic sensor. In particular, it is very important to stably acquire a spectral signal by generating a linear motion of the moving reflector assembly as precise as possible. In addition, by miniaturizing a bulky element in an interferometer, it can have many advantages in portability. In this study, a moving reflector for an optical gas imaging device capable of detecting various harmful gases at a distance was manufactured and performance tests were performed. A moving reflector that satisfies the requirements of the spectroscopic sensor in the optical gas imaging device was manufactured using a voice coil motor and a flexure mechanism. The fabricated flexure mechanism is installed on both sides of the drive unit to realize the requirement of the stroke in the direction of the optical axis and to constrain the movement in the radial direction. A prototype was fabricated through precision machining technique and its performance was tested. The experimental test result shows that the flexure-based moving reflector is capable of motion with its stroke of 0.974 mm and 0.5 Hz. Therefore, optical testing result shows that the proposed flexure-based moving reflector can be applied to the actual spectroscopic interferometer in the future.

Keywords: Moving reflector, Flexure, Voice coil motor, optical gas imaging

1. Introduction

The spectroscopic sensor has been widely used for gas monitoring at a distance and Michelson interferometer unit among the components that make up this spectroscopic sensor plays most important role for the multi-species gas detection. Especially, inside the Michelson interferometer unit, the light path difference between two divided beams which are reflected by a fixed and a moving mirror respectively, is very important for precise detection of various several gases [1,2]. In most cases, the optical path difference is generated by precision electromagnetic actuators which can produce a linear repeated motion of several millimetres and nearly flat motion profile [3]. 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. Also, because of the portability of the spectroscopic sensors, smaller electromagnetic actuators are increasingly being demanded in industrial settings.

In this study, a flexure-based moving reflector with voice coil motor for the gas imaging was designed and fabricated, and a performance test was conducted. A flexure-based moving reflector that can satisfy the required specifications of the spectroscopic sensor was manufactured using voice coil motor and flexure spring with pantograph pattern. By finite element method, these specifications were reviewed in advance whether the proposed flexure-based moving reflector can meet the required specifications or not, for example, the moving distance and yield condition, etc. Also, after fabrication, the performance of the proposed flexure-based moving reflector has been verified in the optical test bench. Especially, for the portability of the spectroscopic sensors, the mechanical structure with small-sized voice coil motor and flexure spring, were proposed. Also, in order to verify the possibility to an actual spectroscopic sensor, its moving distance and tilting error were measured in the optical test bench by measuring the amount of deviation using an autocollimator.

2. Design and testing of flexure-based moving reflector

2.1. Design and manufacture

Our moving reflector assembly is applied to the Michelson type interferometer unit in the spectroscopic sensor as shown in figure 1. Example of the interferometer unit is shown in this photograph. In this interferometer unit, there are several components including moving reflector assembly, fixed mirror assembly, interferometer housing, beam splitter, etc. Among these components, moving reflector assembly performs the function of receiving the incident light from the external environment and reflecting the light to the beam splitter. Meanwhile, fixed mirror can perform the function of reflecting the light in the same way along the other optical path. These optical path difference between these two lights are essential for the precise detection of several gases. Here, moving reflector assembly should make very linear motion along the optical axis and as precise as possible. But this device can have a motion error and this is due to product assembly and other environmental errors. In order to overcome these difficulties, by introducing flexure-based moving reflector, it is possible to prevent the performance degradation and secure the alignment of actual spectral sensor. Also, the user wants to handle the spectroscopic sensor easily, smaller moving reflector assembly should be designed.

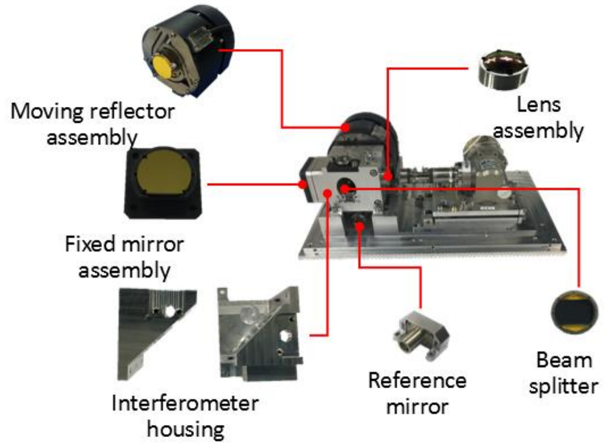


Figure 1. Optical components of Michelson interferometer unit

The moving reflector assembly has several design specifications including moving distance, dimensions and tilting error, etc. It should be able to move at least ±0.5 mm and its tilting error should be below dozens of arcseconds. Also, size of the total assembly should be as small as possible for the portability of the spectroscopic sensor [4]. For these purposes, the moving reflector assembly in this study is equipped with flexure springs at both ends of the voice coil motor to supplement the linear motion. These flexure springs are installed on both sides of the shaft so that the voice coil motor can move in a straight line. Also, the moving distance of the reflector is determined by the thrust of the voice coil motor and the stiffness of the flexure spring. This pantograph flexure spring part with a diameter of 20.9 mm can secure a longer arm length compared to those of other shapes, so the axial stiffness can be designed to be very small. Also, it can bring about an advantage in manufacturing costs using mass production facilities [5,6].

Table 1. Design specifications of flexure-based moving reflector

Name	Items	Design specification
Moving reflector	Moving distance	±0.5 mm
	Dimensions	Ø20 mm X 2.5 mm (mirror)
	Tilting error	10 arcsecond
	Speed	0.5 Hz

Figure 2 shows the flexure-based moving reflector assembly that has been designed for the application of spectroscopic sensor considered in this investigation. The moving reflector holds a flat fused silica mirror with diameter of 20 mm and it is bonded on a mirror adapter guided with two flexure springs. We determined the dimensions of the flexure spring so that the moving reflector assembly can satisfy the design specification by reducing the axial stiffness. Also, we designed the flexure spring with higher lateral stiffness so that its motion should be as straight as possible in the optical axis by reducing the parasitic motion in the lateral direction. Before manufacture, the finite element analysis was performed to predict whether the proposed moving reflector assembly can meet the design specification. Figure 4(a) shows the deformation contour when the force of 1 N is applied in axial(y) direction. As in the analysis result, the axial stiffness is estimated to be 1.30 N/mm which is sufficiently enough to satisfy the design specification of ±0.5 mm. Similarly, figure 4(b) shows the deformation contour when the force of 1 N is applied in lateral(z) direction resulting in the lateral stiffness of 12.9 N/mm. Also, its maximum stress level of 269 MPa at 1 N can be estimated as shown in figure 4(c). Therefore, the stress level when the moving reflector assembly moves at ±0.5 mm is below the yield strength of the material. Also, for the portability as a spectroscopic sensor, the dimensions of flexure springs and other components of the moving reflector were designed as small as possible.

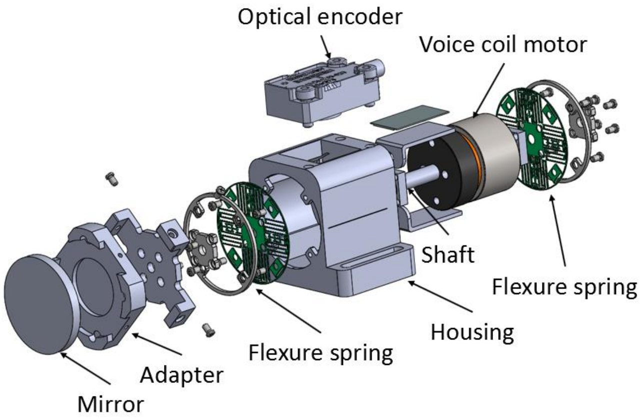
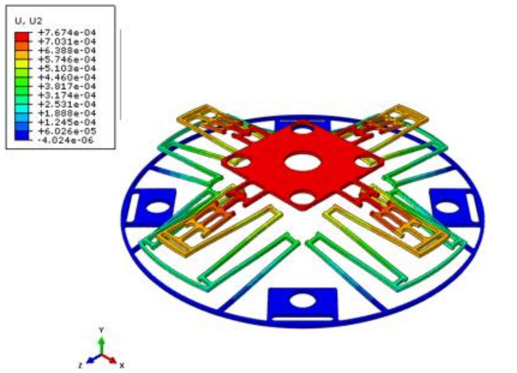
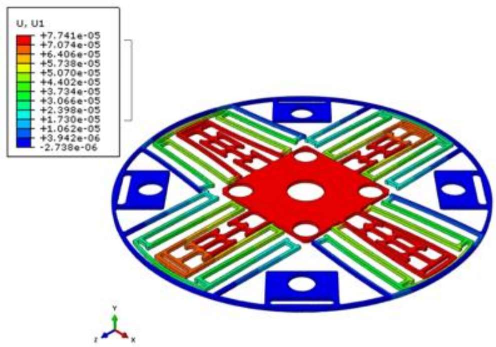


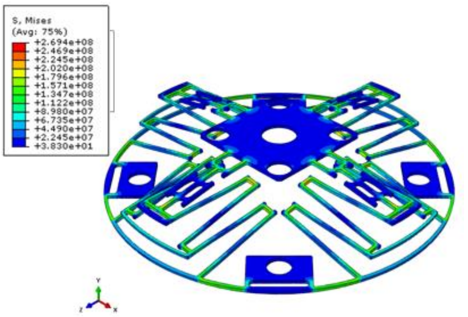
Figure 2. Solid drawings of flexure-based moving reflector assembly



(a) Deformation contour when the axial force of 0.24 N is applied at the center of the flexure



(b) Deformation contour when the lateral force of 1 N is applied at the center of the flexure

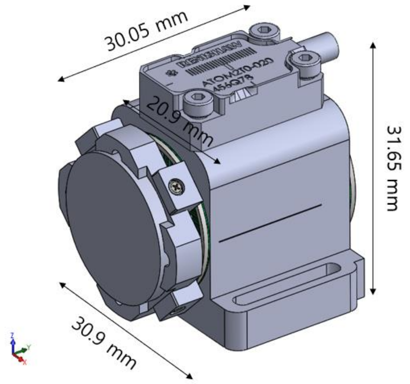


(c) Maximum stress contour when the axial force of 1 N is applied at the center of the flexure

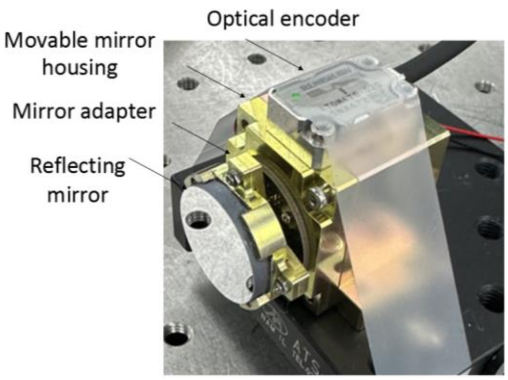
Figure 3. Proposed design of flexure-based moving reflector and deformation contour of the flexure when the mirror was moved

2.2. Testing

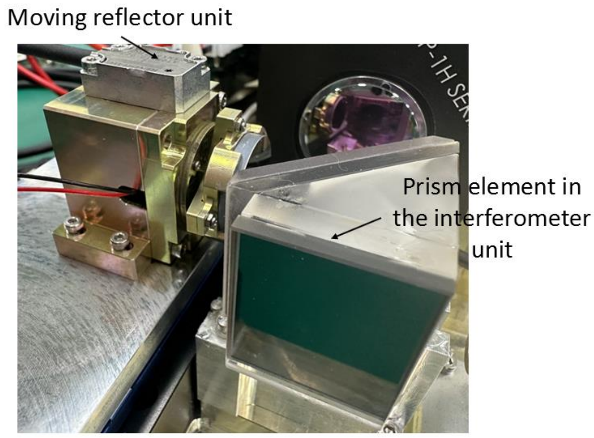
As shown in figure 4(a), the reflecting mirror is moved by voice coil motor with small circular cross-section, whose dimensions are 16x16mm. An optical encoder assembly with high resolution is installed within the moving reflector to measure the linear motion of the voice coil motor, which is subsequently closed loop controlled to compensate for the displacement error. As shown in figure 4(b), a prototype of flexure-based moving reflector was manufactured with a size of 30.9x31.7x30.1 mm, horizontal × vertical × length. It was built with titanium alloy (Grade 5) and the flexure spring was manufactured by wire electrical discharge machining technique. Figure 4(c) shows the photograph of the moving reflector assembly with prism element installed in the interferometer unit for spectroscopic sensor.



(a) Proposed design of flexure-based moving reflector



(b) Flexure-based moving reflector manufactured for spectroscopic sensor

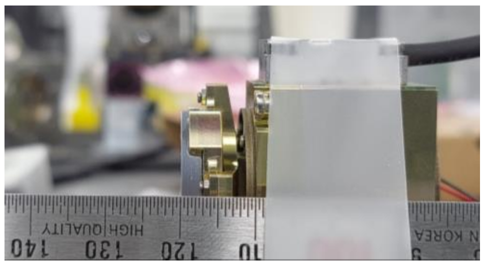


(c) Photograph of the moving reflector assembly installed in the interferometer unit

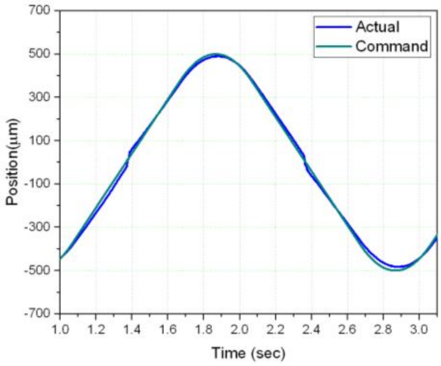
Figure 4. Proposed design and manufactured flexure-based moving reflector with prism element in the interferometer unit

To measure the moving distance of the proposed moving reflector assembly, driving test was performed as shown in figure 5(a). For a sinewave with amplitude of ±0.5 mm and frequency of 0.5 Hz, the moving reflector assembly can move back and forth and its moving distance can be measured by optical encoder mounted inside the assembly housing. As a result of driving test of the moving reflector, figure 5(b) shows that the moving distance was measured to be 0.974 mm at the frequency of 0.5 Hz. The measurement results that do not meet the design specifications are because the actual displacement did not reach the commanded value (±0.5 mm) during the closed-loop control process resulting in an error. In actual operation, these errors can be overcome by resetting the commanded values during actual operation.

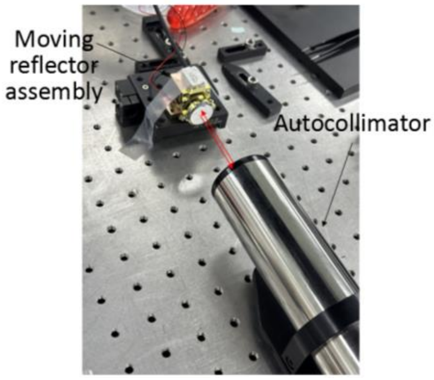
Also, the tilting error of the moving reflector can be measured by applying the autocollimator as shown in the figure 5(c). When the moving reflector moves repeatedly with movement distance of 0.974 mm and frequency of 0.5 Hz, the tilting error was measured by aligning the moving reflector assembly and autocollimator. As a result of the measurement, tilting error of 30 arcsecond was obtained and shows that the proposed moving reflector can be applied to an actual spectroscopic sensor successfully by performing the additional alignment when installing the interferometer unit.



(a) Photograph of the driving test setup of flexure-based moving reflector



(b) Repsonse of proposed moving reflector for a sinewave with amplitude of ±0.5 mm and frequency of 0.5 Hz



(c) Photograph of experimental setup for measurement of straightness by autocollimator

Figure 5. Driving test of proposed moving reflector for a sinewave with amplitude of ±0.5 mm and frequency of 0.5 Hz and photograph of experimental setup for measurement of straightness by autocollimator

3. Conclusions

We designed and manufactured a flexure-based moving reflector in a spectroscopic sensor for optical gas imaging. It is composed of a voice coil motor and flexure springs that generate the axial displacement which is required for the optical path length in the interferometer unit. Also, to minimize the tilting errors, two mechanical flexure springs which can reduce the lateral displacement were installed at both ends. Also, the several dimensions of flexure springs were examined advance by finite element analysis in advance. As a result of the performance test, axial displacement of 0.974 mm was measured at the driving frequency of 0.5 Hz. Also, the moving reflector assembly can move with tilting error of 30 arcsecond by autocollimator. This measurement shows that proposed moving reflector assembly can be applied to an actual spectroscopic sensor successfully.

Acknowledgement

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