

OPTICAL METROLOGY OF MICRO-ELECTRO-MECHANICAL TORSIONAL MIRRORS

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Abstract — An optical reflectometer was designed, built and calibrated for measurement of the dynamics of MEMS resonant torsional micro-mirrors. The resonant frequency of the micro-mirror used for this study was measured as 3.997 kHz, the maximum rotation angle was measured as $\pm 4.32^\circ$ ($\pm 8.64^\circ$ optical) and the quality factor (Q) was measured to be 88.8. The mechanical behavior of the MEMS torsional mirror, including normal modes, frequency and static response, were simulated by using finite element analysis (FEA) software MSC NASTRAN/PATRAN. The computed resonant frequency is within 0.1% of the measured frequency. The computed rotation angle is within 6% of the measured angle.

Key words — Micro-Electro-Mechanical Systems (MEMS); Optical metrology; Reflectometer; Finite element analysis; Torsional micro-mirror.

I. INTRODUCTION

Precise characterization of the dynamic mechanical response is a primary concern in MEMS metrology. Dynamic parameters such as displacement, rotation angle, resonant frequency and quality factor must be determined for better understanding of MEMS devices. However, the size of MEMS structures and their high frequencies make measurements difficult. As a result, there is a need for the development of metrology tools specifically designed for the dynamic measurement of MEMS devices. This research employs a laser reflectometer to measure the motion of a MEMS mirror, and compares the experimental results with FEA calculations.

II. DESIGN OF MICRO-MIRRORS

Torsional scanning micro-mirrors are small, highly reflective, and offer interesting opportunities for small display devices used in head mounted displays [1]. Fig. 1 shows the schematic of the torsional mirror designed by the MicroOptical Engineering Corporation (Westwood, MA). The mirror was fabricated at the Northeastern University (Boston, MA) Microfabrication Laboratory [1]. The central mirror is 1 mm on a side and about 20 μm thick. The mirrors are electrostatically driven at frequencies in the range from 4 to 8 kHz and can achieve mechanical rotation angles up to $\pm 4^\circ$ ($\pm 8^\circ$ optical) at their resonant frequencies [1].

The mirror body is made out of single silicon substrate material by bulk micromachining. The thickness, mass, and stiffness of the mirror are defined by a patterned etch from the backside of the wafer. An etch from the front defines the mirror's length and width. To support and actuate the mirror, two torsional support bridges are made by electroplating nickel on top of the silicon layer. Two anchors connect each support bridge to the wafer and the mirror, and also serve as the actuators. These anchors are equal in height and define the gap of the actuating

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capacitors. Two electrodes underneath each bridge and on either side of the axis of rotation can be used either to excite or sense the motion of the mirror. The actuation of these devices is electrostatic. The actuating electrostatic force is provided by applying a voltage to one of the electrodes on the wafer surface and grounding the mirror support electrode. This force results in a torque which then causes the mirror support and mirror to rotate. The sensing electrode is used to detect the motion of the mirror by measuring the capacitance [1].

III. DESIGN OF OPTICAL REFLECTOMETER SYSTEM

Reflective sensing is widely used in measurement applications, because of its characteristics of high accuracy, simplicity, and non-contact. The photograph of the reflectometer arrangement is shown in Fig. 2. A light beam from a solid-state laser is focused through a pinhole, passes through focusing lenses, and converges to a spot of 20 μm in diameter on the mirror surface. The incident light spot can be positioned on the center of the oscillating mirror by carefully adjusting the mirror position under a microscope. A second lens refocuses the reflected light on a transmission screen which is imaged by a computer-based CCD camera. The image is a streak, whose length is proportional to the angle through which the driven mirror oscillates. A commercial image analysis software, namely the Andromeda Measurement Filter, is used for the construction of the calibration curve based on the characteristics of the focused spot from the mirror when it is stationary, and to measure the extent of the streak formed by the oscillating mirror. A micrometer-controlled calibration device was used to relate the mirror deflection angle to displacement of the reflected and focused light along the screen.

IV. MEASUREMENT AND DATA ANALYSIS

A. Calibration

The output signals of the laser reflectometer system are optical streaks, with length determined by the angle through which the driven mirror oscillates. The length of the optical streak on the screen should, preferably, be linearly related to the rotation angle of mirror surface. Linearity depends upon the geometry and placement of the screen, the quality of the optics system used to refocus the light spot onto the screen, and on the quality of the CCD camera, i.e. any optical distortion introduced by camera lenses. A calibration function or table over the whole angular range must be employed to correct for non-linearity.

The calibration device consists of a glass plate reflector, provided with a micrometer is used to control its displacement and rotation angle. To generate the rotation, the micrometer is used to move a probe tip, which presses down on the glass plate. A spring underneath the glass plate ensures tight contact between the probe and the glass plate. Displacement as small as 1 μm can be achieved at the probe tip, corresponding to an angle of 0.0056° . The resultant displacement of the laser dot in the image is captured by the CCD camera and used to calibrate the system.

B. Rotation Angle and Resonant Frequency Measurements

The maximum rotation angle and resonant frequency can be determined by measuring the length of the light streak as a function of excitation frequency. For this data, the rotation angles can be obtained using the calibration curve obtained. The resonant frequency is the frequency where rotation angle achieves the maximum value. The averaged data from several measurements are shown in Fig. 3. The resonant frequency of the mirror is found to be 3.997 kHz. The maximum full sweep rotation angle of the mirror was 4.32° . The quality factor (Q) of

the system can be obtained by measuring the frequency bandwidth (B) about the resonant frequency. The quality factor is calculated as 88.8. The relationship between rotation angle and drive voltage magnitude was studied by varying the magnitude of drive voltage from 65 V to 170 V (peak). The frequency of drive voltage was fixed at the resonant frequency of 3.997 kHz. The result curve shows a non-linear behavior as expected. The force in an electrostatic actuator is a function of V^2 , where V is the drive voltage.

The experimental rotation angle vs. frequency curve can be decomposed into several components to study the dynamic characteristics of the micro-mirrors. For this mirror the response contains six decomposed curves, as shown in Fig. 3. It can be seen that most of the additional components in the response are at frequencies higher than the resonant frequency. The best fit number and location of the peaks can vary depending on the specific operations used to calculate the decomposition of the averaged data. Hence, these details are less important than the appearance of the additional near-resonance peaks.

V. FEA SIMULATION OF MICRO-MIRRORS

Normal mode, frequency response, transient response and static simulations of the micro-mirrors were done by using FEA program MSC NASTRAN/PATRAN [3]. The resonant frequency of the mirror was calculated to be 3.994 kHz. This value is within 0.1% of the measured resonant frequency of this micro-mirror, which is 3.997 kHz.

In frequency response simulation, the micro-mirror was excited under a frequency-varying excitation in a range of 0 ~ 300 kHz. A damping factor of $\zeta = 0.006$ is used. The result shows the micro-mirror reaches a resonant peak at 4.02 kHz, a second peak at 20.32 kHz and a third peak at 38.46 kHz. The maximum displacement of the edge of the mirror is 40.03 μm at the resonant frequency. The rotation angle at the resonant frequency can be calculated as 4.58°. This value is within 6% of measured maximum rotation angle of 4.32°. The error is mainly due to the selection of the damping factor. Since the mirror was packaged in a vacuum, a small damping factor of 0.006 is used in this work. However, the damping factor of 0.006 is not verified and it is not an accurate value. This simulation shows that the real structural damping factor may be slightly larger than 0.006.

To compare the dependence of rotation angle on the drive voltage, the drive frequency was set to the measured resonant frequency of 3.997 kHz. Simulation shows the FEA result values are slightly higher than experimental curve. The rotation angle difference between the two curves is 0.1°. The simulated maximum rotation angle is 4.4°, which is within 2.3% of the measured value. The result of this simulation also verifies that the structural damping factor 0.006 is smaller than the actual damping factor of the device. Had we increased the damping factor to some extent, the simulation result would have matched the experimental result more precisely.

VI CONCLUSIONS

Measurements, simulations and analysis were employed to characterize a MEMS torsional mirror. The resonant frequency of a micro-mirror was measured to be 3.997 kHz, the maximum rotation angle was 4.32°, and a quality factor (Q) of 88.8 was obtained from the frequency response data. The computed resonant frequency is within 0.1% of the measured frequency. The computed rotation angle is within 6% of the measured angle. Simulation shows the damping factor of 0.006 is smaller than the actual damping factor of the device. The reflectometer and NASTRAN were proved to be effective experimental and computational tools. The micro-mirror exhibited a more complex frequency dependence than expected. Its origin is not understood.

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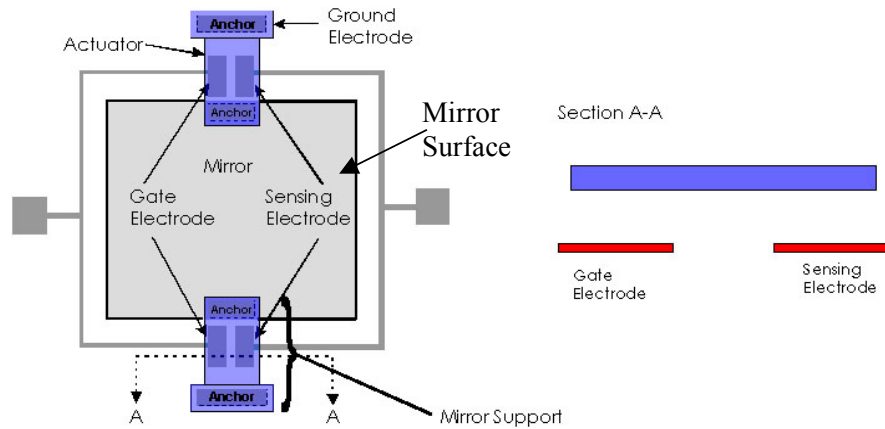


Fig. 1. Schematic of the Torsional Mirror.

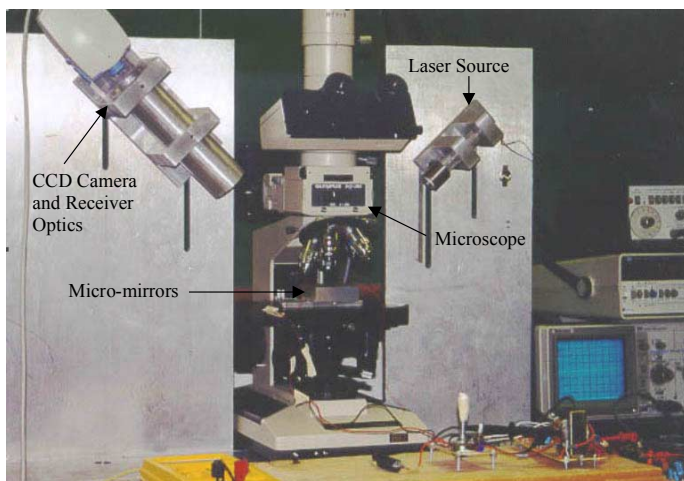


Fig. 2. Photograph of the Optical Reflectometer.

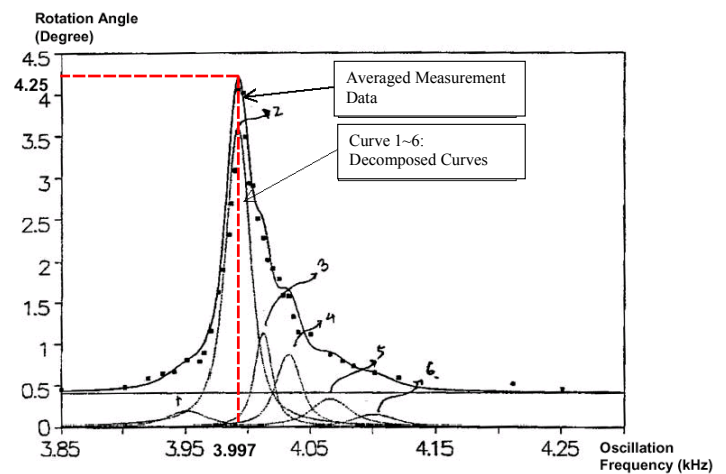


Fig.3. Component Peaks in Micro-mirror Frequency Response Curve.