MEMS Mirrors for automotive applications

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Abstract—**Microelectromechanical system devices are widely employed in automotive electronics because of its low cost, small size and high functionality. Cars are going to be equipped with optical components, especially micromirrors to realize intelligent safety, driving and communication systems. The mechanical reliability of the micromirrors should be addressed, which is discussed in this manuscript.**

Keywords-micromirror; MEMS; automotive application; display; lighting; LiDAR; reliability

I. INTRODUCTION

Micromirror devices are devices which consist of a single mirror or arrayed miniaturized mirrors to control intensity and direction of light for various optical systems, such as video projection [1], optical communication [2], lighting equipment [3], and object detection / ranging [4]. Micromirror devices have been extensively developed based on microelectromechanical system (MEMS) technologies because of its mass-production, circuit-integration, low-cost and miniaturization capabilities [5]. Since those benefits attracts strongly for automotive industries, application to automotive electronic system have been considered widely. Major applications of MEMS-based micromirror devices are going to be presented and the mechanical reliability, one of the most important issues for automotive components is discussed.

II. MEMS MICROMMIRRORS

A mirror plate tilts for one direction (1D) or any angles (2D) to steer the reflecting light. The plate is suspended by torsion beams aligned along the rotating axis of the mirror or supported by bending beams at its outer edges for free tilting mirrors. Structures are often made of silicon, because of its high relative stiffness (low density and high elastic constant) and high yield strength, which allows us to operate it with a large tilting angle at a high operating frequency. The major driving principles are piezoelectric, electrostatic and electromagnetic actuations. Digital (On/Off) and continuously tilted operations are possible. Arrayed small (~100 μm square) mirrors are often operated by electrostatic force, because of simple structure and easy operation [1]. Large (~10 mm in diameter) tilting mirror are actuated piezoelectrically [6] or electromagnetically [7] because of their larger actuation force. More comprehensive review articles are available, such as [5].

III. AUTOMOTIVE APPLICATIONS

A. Display

Configurable dashboard and head-up display (HUD) present speedometer, tachometer, and navigation information on a dashboard screen or front window. Especially HUD can provide information to driver without moving the line of sight, which increases the safety and reduces driving stress [8]. Micromirrors are one of the candidates for imaging devices of the systems.

B. Intelligent Headlight

To reduce traffic accidents in nighttime driving, high beams should be used for detecting objects. However, high beams may dazzle others, such as pedestrians and drivers in opposing cars. To avoid dazzling, intelligent (adaptive) headlight system in which lighting area is controlled using micromirror devices not to illuminate these objects without changing to low beams. In addition, the system can control direction arbitrarily by adapting the speed, inclination, and cornering [3].

C. LiDAR

Light detection and ranging (LiDAR) is system that detects surrounding objects by emitting light and detecting reflected light and ranges them by means of time-of-flight principle. The system has been developed in intelligent transportation system (ITS) [9], but recently attracts much attention for the application of autonomous driving [10]. MEMS micromirrors are going to be adopted for scanning light, instead of polygon mirrors or rotating mechanism.

IV. RELIABILITY

All these automobiles and any applications strongly demand performance improvement of micromirrors, such as wider deflection angle, higher speed, and larger mirror size. The deflection angle determines the field of view (FoV) or image size. Though the image size fulfills the requirements, system developers always request larger angle that makes optics compact. The speed or frequency determines the frame rate. Since optical resolution relates the aperture of optics, larger mirror is required for clear image and sensitive detection.

Therefore, we need a wider, faster and larger mirror device but these improvements shows tradeoff relationship and more significantly they cause critical issues of reliability. Three main reliability issues are discussed

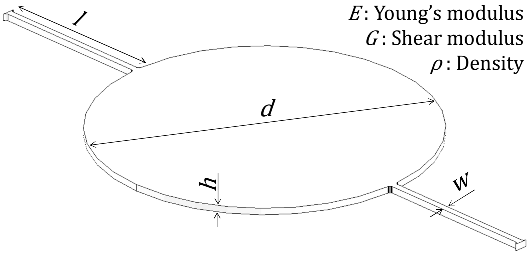

Figure 1. Example of torsional resonant micromirror

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below. To describe it, a single-direction, torsional mirror structure presented in Fig. 1 is used. The moment of inertia J of the mirror plate is,

$$J = \frac{1}{32}\rho\pi d^4 h\,. \qquad (1)$$

Assuming $w \geq h$, the torsional stiffness k_θ of a beam is,

$$k_\theta = \alpha G\frac{wh^3}{l}\,, \qquad (2)$$

where α is a function of w/h ($\alpha = 0.229$ at $w/h = 2$). The resonant frequency f_t of the torsional vibration is;

$$f_t = \frac{1}{2\pi}\sqrt{\frac{2k_\theta}{J}} = \frac{1}{2\pi}\sqrt{\frac{64\alpha G h^2 w}{\rho\pi d^4 l}}\,. \qquad (3)$$

When we need larger mirror plate without sacrificing resonant frequency, the stiffness should be proportionally increased with 4th power of the diameter. To operate this enlarged mirror, much higher actuation force is required.

A. *Fracture and Fatigue*

As we discussed above, high performance micromirror devices have stiff torsion beams, which means that the shear stress on the beams may become critical on the operation. The maximum shear stress τ_{max} on the beam is appeared at the center line of the top surface if the width w is larger than thickness h;

$$\tau_{max} = \beta G\frac{h}{l}\theta\,, \qquad (4)$$

where b is a function of w/h ($\beta = 0.931$ at $w/h = 2$). Apparently, a stiff beam having shorter and thicker beam has higher risk of failure.

Because silicon is a brittle material, fracture happens suddenly and catastrophically. Since fracture is originated from defects or flaws in torsion beams, the fracture criteria, strength may have deviations. Therefore, in order to ensure the reliability, statistical analysis of the strength and design considering safety factors are required [11]. Fatigue fracture is also concerned. Especially, moisture degrades significantly the fatigue strength and lifetime [12].

B. *Nonlinearity*

On large deflection angle operation (mechanically 15~20 degree), nonlinearity becomes significant due to large deformation effect in the stiffness, non-uniform actuation force and asymmetry of the structure. The simplest equation of motions with external momental actuation $M(t)$ for expressing nonlinearity is;

$$J\ddot{\theta} + C\dot{\theta} + k_\theta\theta + k'_\theta\theta^3 = M(t)\,, \qquad (5)$$

where C is dumping coefficient and k'_θ is nonlinear stiffness. When k'_θ is positive, the stiffness increases by increasing deflection angle and resonant frequency increases, called hard spring effect. When k'_θ is negative, change goes the different direction (soft spring effect). In both case, the frequency response has hysteresis and resonant vibration becomes unstable near the resonant frequency. Even in similar device structure, both types of effect were observed [10][13], so the control and reduction of the effect is often difficult.

C. *Mirror deformation*

On enlarging the mirror size, the mirror plate deformation should be considered, especially faster operation. The peak to valley surface deformation δ for rectangular mirror plate at the vibrating amplitude θ_0 and angular frequency ω is,

$$\delta = \frac{0.009\rho\theta_0\omega^2 d^5}{Eh^2}\,. \qquad (6)$$

The deformation should be smaller than $\lambda/16$ (λ : wavelength) , considering the Rayleigh limit [14].

V. CONCLUSIONS

MEMS micromirrors are going to be used in automotive electronic systems, which realize intelligent cars. The mechanical design, especially the reliability is a key for development of high performance micromirrors and the automotive optical systems.

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