ABSTRACT

This paper presents a sliding mode control scheme to improve the positioning performance of a 2-Degree-of-freedom (DOF) torsional MEMS micromirror with sidewall electrodes. The stability of closed-loop system is proved by Lyapunov stability theorem under the existence of bounded parameter uncertainties and external disturbances. Furthermore, the performance of the closed-loop system is illustrated by experimental and simulation results which verify that the feasibility and effectiveness of the proposed scheme. The results demonstrated that the torsional MEMS micromirror with the proposed sliding mode controller has a good transient response and tracking performance.

Keywords: 2D Torsional MEMS Micromirror, Field Programmable Gate Arrays (FPGAs), Microelectromechanical Systems (MEMS), Sidewall Electrodes, Sliding Mode Control (SMC)

INTRODUCTION

MEMS mirrors are adopted in widespread applications in recent years, such as optical switches, adaptive optics, high definition display and imaging systems. These devices are highly depended on the performance of MEMS mirrors. Though a variety of actuation techniques such as electrostatic, electrothermal, piezoelectric and electromagnetic exist, the major advantages of electrostatically actuated micromirrors are standard MEMS fabrication, compact size, low power consumption and high reliability.

The analysis of electrostatically actuated torsional micromirrors have been extensively studied. Zhang, Chau, Quan, Lam, and Liu (2001) studied the static characteristics of an

Several approaches have been used for overcoming the well-known pull-in instability phenomenon (Yazdi,Sane, Kudrle, & Mastrangelo,2003; Chen, Weingartner, Azarov, &Giles, 2004; Zhao, Tay, Chau, & Zhou, 2006; Agudelo, Packirismay, Zhu, &Saydy,2009). Besides extending the stable operational range beyond the pull-in position, nonlinear feedback control techniques have been also reported to improve the scanning performance of micromirrors. Pan, Ma, and Islam (2008) proposed the nonlinear proportional and derivative (PD) control and gain scheduling method to improve the performance of mirror switching. Sun, Yeow, and Sun (2012) presented an internal model approach to address the output-error-constrained tracking problem of electrostatic actuator. Agudelo, Zhu, and Saydy (2007) proposed a nonlinear closed-loop control to obtain stable operations in the whole range of deflection. The flatness-based technique is used for tracking control of torsional micromirror (Agudelo, Zhu, Packirismay, & Saydy 2007). Zhao, Tay, Zhou, and Chau (2006) reported a multi-loop digital control method to improve the positioning performance of dual-axis micromirror. Sliding mode control (Sane, Yazdi, & Mastrangelo, 2003; Zhao, Tay, Chau, & Zhou, 2006) also has been successfully applied to torsional micromirrors.

In this paper, a sliding mode control (SMC) scheme is employed to improve the transient dynamics of a 2D torsional micromirror with sidewall electrodes. The mathematical model is introduced to describe the electrostatically actuated 2D torsional micromirror with sidewall electrodes in the first section. The proposed SMC controller is presented afterwards, the stability of the closed-loop system is proved by Lyapunov stability theorem. The simulations and experimental results are given in the following section. Finally, the conclusion is discussed.

**DYNAMIC MODEL**

The 2-Degree-of-freedom (DOF) torsional MEMS micromirror with sidewall electrodes, illustrated in Figure 1 and Figure 2, consists of a mirror plate, gimbal frame, torsion bar, bottom and sidewall actuating electrodes. The micromirror is suspended by a double-gimbal structure and actuated by electrostatic torques. The mirror plate rotates about two axis depending on the actuation voltages applied to the bottom and sidewall electrodes.

\[
\begin{align*}
(J_1 + J_2)\ddot{\alpha} + D_1\dot{\alpha} + K_1\alpha &= T_\alpha \\
J_1\ddot{\beta} + D_2\dot{\beta} + K_2\beta &= T_\beta
\end{align*}
\]

(1)

where \(\alpha\) and \(\beta\) are tilt angles, \(J_1\) and \(J_2\) are the mass moment of inertias of the mirror plate and gimbal respectively. \(D_1\) and \(D_2\) are the damping coefficients, \(K_1\) and \(K_2\) are the stiffness coefficients. The total electrostatic torque \(T_\alpha\) and \(T_\beta\) are given as

\[
\begin{align*}
T_\alpha &= \sum_{i=1}^{4} T_{E1_i}^E + \sum_{i=1}^{4} \sum_{j=2}^{3} T_{E1_{i,j}}^E + \sum_{i=1}^{4} T_{E2_{i}}^E \\
T_\beta &= \sum_{i=1}^{4} T_{E1_i}^E + \sum_{i=1}^{4} \sum_{j=2}^{3} T_{E1_{i,j}}^E
\end{align*}
\]

(2)

where the electrostatic torques from the bottom electrodes, and sidewall electrodes on the mirror are \(T^E\) and \(T^E_{sidewall}\). \(T^E_{sidewall}\) is the electrostatic torques from sidewall electrodes on the gimbal frame.

\[
\begin{align*}
\sum_{i=1}^{4} T_{E1_i}^E &= \frac{1}{2} c_{E} \sum_{i=1}^{4} v^2 \int_{x_{E}} \sin \phi \frac{1}{g - z \cos \alpha \sin \beta + y \sin \alpha} dy \\
\sum_{i=1}^{4} T_{E1_{i,j}}^E &= \frac{1}{2} c_{E} \sum_{i=1}^{4} v^2 \int_{x_{E}} \sin \phi \frac{1}{g - z \cos \alpha \sin \beta + y \sin \alpha} dy
\end{align*}
\]

(3)
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