Modeling and Dynamic Simulation for Electrostatically Driven Micromirror

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ABSTRACT

Dynamic behavior of the electrostatically driven bi-directional micromirror system was simulated with ANSYS parametric design language. The objective of the study is to construct a dynamic simulation scheme for the transient properties of electrostatically coupled mechanical system. Iterative method between the electrostatic and mechanical analyses with a small increment of time (*Dt*) was used for this simulation.

In the simulation, shell element was used for the structural modeling. Air components using solid elements were added between the bottom electrodes and mirror plate for the electrostatic force calculation.

Comparison between the simulated results and experiment data showed good agreement. Result of this work can be applied to the analysis of electrostatically driven microsystem helping to design more effectively.

Keywords: micromirror, ANSYS, electrostatic, transient.

1 INTRODUCTION

Electrostatic force is a popular methodology to drive micro actuator because of its simplicity and fast response time. Especially, in the case of display device, which requires repetitive arraying and separate control as well as fast actuation speed, the low level of structural requirement for electrostatic actuation makes it a best choice.

A spatial light modulator that changes the direction of reflected light by electrostatic attraction has been under investigation for long time and one of them had been commercialized successfully. New design of micromirror structure employing bending spring hinges with unique arrangement is currently under development.

In order to estimate the performance and behavior of realized micromirror system, simulation scheme was needed to developed. The micromirror structure under development features bending spring hinges, which doesn't have fixed rotation axis and contact problem of spring tips with landing substrate when the mirror is tilted. The simple lumped method, therefore, could not be applied and Dynamic transient analysis based on Runge-Kutta method has been performed, and its results are reported.

2 MICROMIRROR STRUCTURE

The micromirror system, as shown in Figure 1, is largely consisted with three parts; bottom electrodes, spring hinges and various supports, and mirror plate. The bottom electrodes supply electricity and control. Two bending spring hinges are vertically separated from the bottom electrodes with a pair of posts and a rigid member, called 'Girder'. These spring hinges, girder, and other posts form the mechanical part of the structure. The elastic energy stored in spring hinges during actuation give rise to restoring force oppose to the electrostatic driving force generated by the electric potential between bottom electrodes and mirror plate. The whole mirror structure is constructed with aluminum alloy to pass through electricity all the way up to the mirror plate. Another function of the mirror plate is to reflect light [1]. Tilted mirror plate by the electrostatic force enables the system to change the direction of the reflected light. As the mirror tilts, protruded tips of girder land on the substrate to stop the mirror plate and define the tilt angle. These tips are the final element of the structure, and its function is to ease the release of the girder from the contact to the substrate.

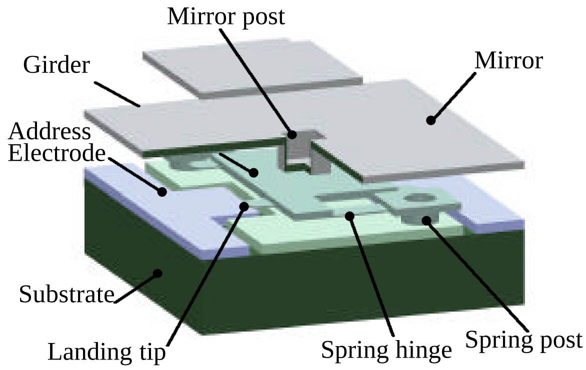

Figure 1: Schematic drawing of micromirror with 1/4 of mirror plate removed to show detail.

2.1 Modeling

Both the electrostatic and mechanical models were required to simulate the dynamic characteristics of micromirror system. Electrostatic and structure transient analyses were performed to obtain electrostatic force and deformed structural shape by the force, respectively.

The suitable element for performing a current conduction analysis was the SOLID 5, 3D coupled field solid element, so it was used for electrostatic modeling of the air. And for its large deformation capability, SOLID 45 element was used for the structural analysis with exactly the same geometry of the electrostatic one. SHELL 157 element was used for the electrostatic analysis of aluminum conductor. SHELL 63 element was used for the structural transient analysis of aluminum structure. Additionally, the structural model included CONTACT49 elements, as shown in Figure 2, to solve contact problem of the landing tip with the common electrode on the substrate. 4-node shell and 8-node solid elements can share their geometry data and nodal numbers.

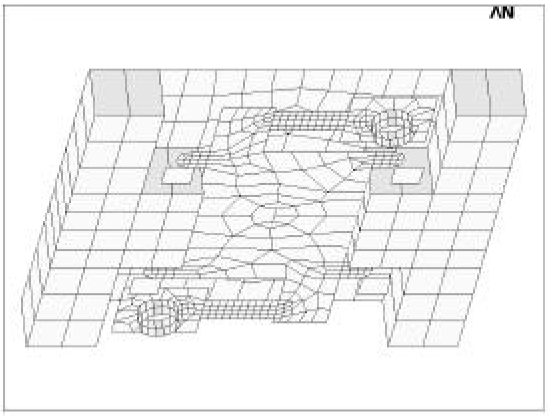

Figure 2: Mesh plot of simulation FE model.

2.2 Principles of micromirror actuation

The system is driven by electric field generated between two opposing electrodes in the form of electrostatic force. One of the electrodes is the mirror plate to which driving voltage is supplied, and the other is bottom electrode at the substrate. Two bottom electrodes are supplied with either 5 or 0 volts to address the pulling direction. Then, as the driving, or biasing, voltage is applied to the mirror plate the electric potential difference of one side is 5V greater than the other causing the mirror to tilt to the greater side, as shown in Figure 3.

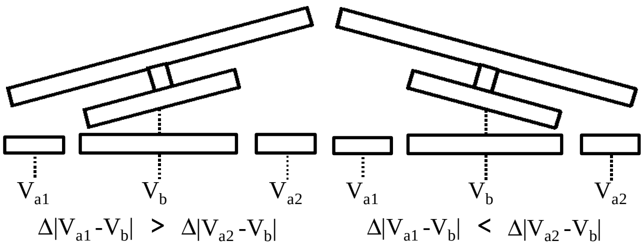

Figure 3: Conceptual drawing of micromirror actuation. Mirror rotates toward higher potential difference.

Release of tilted mirror is accomplished by the combined mechanical force of bending spring hinges and landing spring tips. The major recovery force is coming from the spring hinges. However, in the microscopic system like this, adhesion force at the contact could be larger than the mechanical force of spring hinges, and the spring tips enable the system to break free.

With switched addressing voltage and temporary removal of biasing voltage, the mirror plate is released from its tilted position and tilted to the other side consequently changing the direction of reflected light.

3 PROCEDURE OF SIMULATION

Electrostatic coupled structural transient analysis was used to calculate the resulting deflection as a function of time and input voltage change. Employed non-standard analytical procedure consists of solving the electrostatic problem by field analogy using one database and applying calculated nodal electrostatic forces to a structural transient analysis in a second database. Structural displacements were then used to update nodal coordinates in the electrostatic database at the beginning of a second solution cycle. This was done to account for the effect of changing geometry on field strength and resulting electrostatic forces. Solution cycles were continued until the end of simulation time.

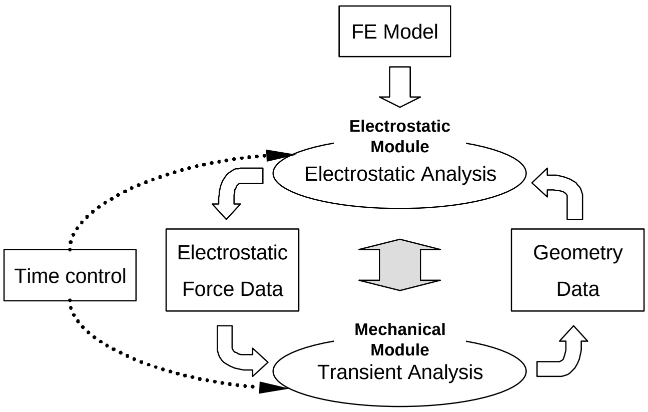

Figure 4: Flow chart of simulation process.

The electrode gap is determined by the amount of mirror rotation. That is, the electrostatic field solution produces the forces, which drive the structural solution, and the resulting structural displacements alter the electrostatic field solution. A 3D structure transient analysis, which takes this effect into account, was desired.

Electrostatic analyses are performed by field analogy. Poisson's equation governing electrostatic field is solved by ANSYS in both heat transfer and current conduction analysis [2]. An appropriated substitution of analogous material properties, boundary conditions, and loads in either a heat transfer or current conduction analysis can be used to perform an electrostatic analysis.

In this effort, a current conduction analysis was used to solve for the electrostatic field. The relationship between electrostatics and current conduction is summarized in Table 1.

SWS C360 visualize workstation with ANSYS 5.6 Mechanical-EMAG3D version was used. Novel APDL program was developed for this simulation.

Table 1: Interpretation of ANSYS command labels in electrostatic and current conduction analyses.

Aspect of analysis	Electrostatics	Current conduction
Governing Eq.	$\nabla \cdot (e \nabla V)$	$\nabla \cdot \left(\frac{1}{d} \nabla V \right) = \frac{\partial r}{\partial t} = 0$
Nodal DOF	V	V
Nodal "loads" and "reactions"	Q: nodal charge	I: nodal current
Material Property	$\frac{1}{e} \left(\frac{1}{permittivity} \right)$	$d\,(resistivity)$
Field intensity E	$-\nabla V$	$-\nabla V$

4 RESULT AND DISCUSSION

4.1 Simulation condition

Value used for Young's modulus of entire structure, including the spring, is 70GPa which is the value for the bulk aluminum. As a separate experiment, an effort to measure the Young's modulus is being carried out utilizing cantilever beam array.

The micromirror system has narrow gap between moving mirror plate and fixed substrate underneath. Squeeze film mode of damping force is known to be the most dominant effect for this kind of system. Damping coefficient of micromirror was calculated from response measurement of natural frequency mode with impulse signal. This coefficient can be changed according to the angular velocity of mirror rotation because of air damping effect. Damping coefficient changes are neglected because simulation has been performed near natural frequency range [3, 4].

4.2 Fabrication of micromirror array

Two address electrodes and a common electrode, which supply bias voltage to upper electrode through the spring and mirror post, are first Al-sputtered and patterned on an oxide-insulated substrate. Photoresist is then spin coated as a lower sacrificial layer and via holes are formed for spring post. The spring and the girder layers are formed with two different thickness with aluminum. Upper sacrificial layer is then applied in the same manner with the lower one. After sputtering aluminum and patterning of mirror plate, both sacrificial layers were removed by plasma ashing. Finished micromirror structure is shown in Figure 5.

Specially designed laser optics system is used to evaluate the performance of micromirror system [5]. Position sensitive detector was used to record the position change of the reflected laser beam due to the mirror tilt angle.

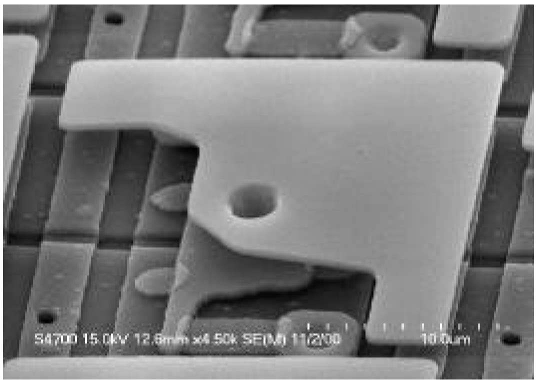

Figure 5: SEM micrograph of fabricated micromirror. A part of the mirror plate is cut off to reveal the underlying structure.

4.3 Analysis of micromirror response

Four different types of mirror operation are investigated to evaluate the modeling and simulation. The trajectory of rotation angle as function of time represents results of motion simulation as well as measurement on Figures 6~9. In the figures, it is shown that the motion simulations are in good agreement with experiment results with the exception of the crossover transient in Figure 8.

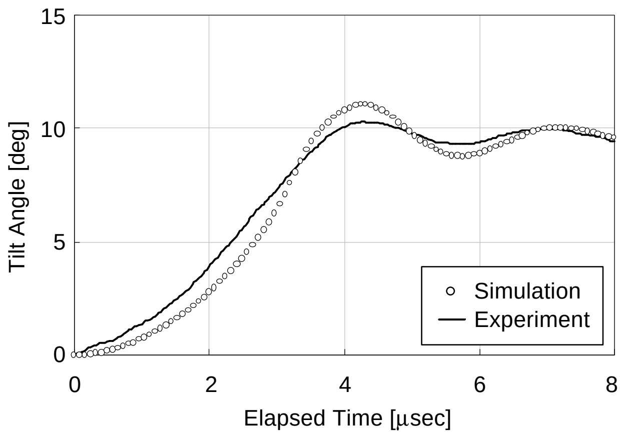

Figure 6: Raising response of micromirror from neutral to full tilt position.

With the step function of bias voltage applied, the response of mirror from equilibrium position to full tilt to land on the substrate is shown in Figure 6.

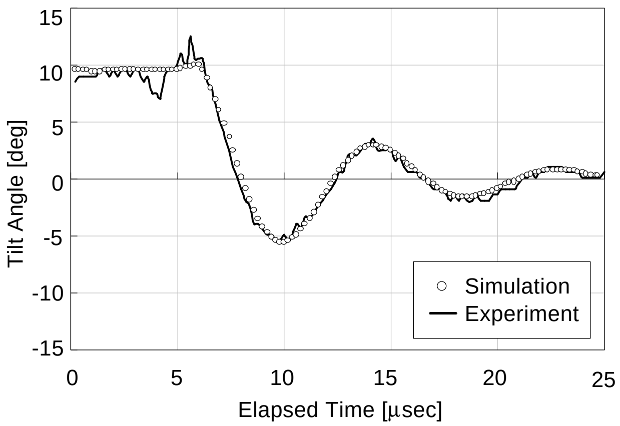

Figure 7: Release response of micromirror from full tilt to neutral position.

Release time stand for the speed of returning mirror from the maximum tilt position as the bias voltage removed. Damped free vibration of mirror was observed in this situation. The natural frequency of mirror calculated from its period of vibration was 113 kHz, and the damping ratio from the logarithmic decrements of amplitude was 0.164. Figure 7 shows excellent fit to the experiment.

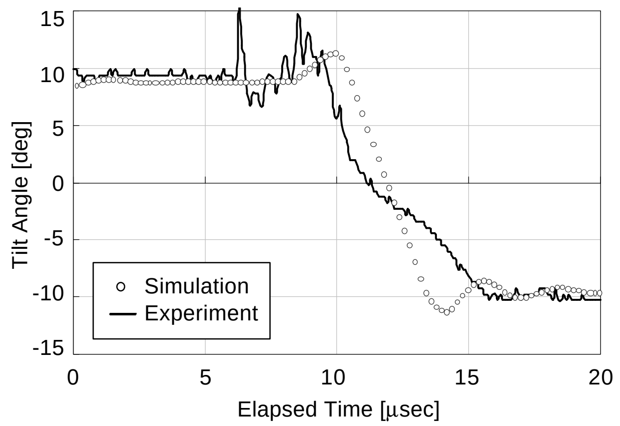

Figure 8: Crossover response of micromirror flipping from one side to the other.

Mirror traverses bi-directionally, crossover transient, to change direction of reflected light with its maximum angle. To change position of mirror from one side to the other, releasing and raising operation should be happen successively. The crossover response is not exactly matched as shown in Figure 8. These mismatches are still under investigation. Current assumption is that interference noise from rapid change of input signal is one of the causes, as shown in the period of 6μsec~9μsec of Figure 8. This noise could disturb the initial state of micromirror, so the subsequent motion differ from ideal case. The last case of evaluation is the stay transient. Even in this case, short pulse of bias is applied due to the driving scheme. Figure 9 shows both the experiment and simulation are in good control.

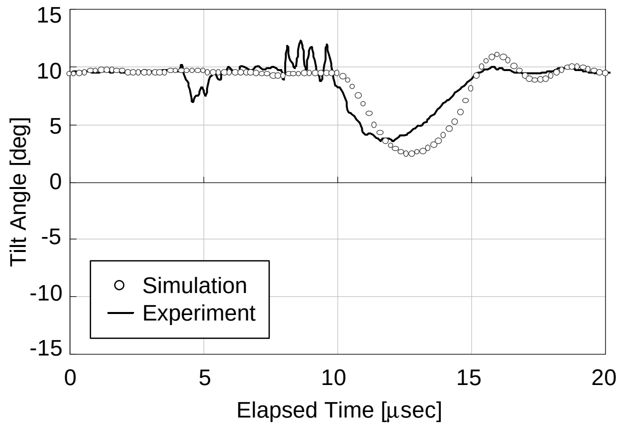

Figure 9: Stay response of micromirror maintaining its initial tilt side.

5 CONCLUSION

Modeling and simulation of electrostatically driven micromirror has been performed and confirmed with experiment. It is also shown this modeling and simulation technique can be applied to the analysis of electrostatically driven micro system helping to design more effectively.

This design technique is currently being applied to the different size of micromirror model. Further study of simulation will be carried out including stiction force effects, high-speed simulation and design optimization.

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