Thermal Stability Simulation of MEMS Micro Scanner
Multi-physics Simulations Coupled with Experimental Verifications

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Abstract: A practical application of multi-physics simulations was presented. In order to analyse thermal stability of MEMS micro scanner, multi-physics simulation procedure was proposed and then verified by comparing the simulated results to the measured data. The proposed procedure started from defining simulation parameters and was verified stepwise by comparing the interim results with the related experimental data, which has increased the accuracy of the proposed, multi-physics simulation procedure. Based on those results, we could got more insight into the thermal stability issue and the allowable bias limit could be determined, which does not deteriorate the device performance significantly. The proposed simulation procedure is expected to contribute for successful commercialization of MEMS micro scanner by increasing its thermal stability.

1 INTRODUCTION

Continuously progressed miniaturization technology, combined with MEMS (Micro-Electro-Mechanical System)-based micro scanner, made it possible to realize pico projector (Davis *et al*, 2008). Furthermore, it has recently gotten a huge amount of interest due to the emerging era of virtual reality (Saeedi et al., 2014). Among major components consisting of pico projector, micro scanner plays a core role of scanning images on optical plane. Except pico projector, micro scanner have also lots of applications such as Light Detection And Ranging (LIDAR) (Moss et al., 2012), optical coherence tomography (OCT) (Strathman et al., 2015), and other medical applications (Pengwang et al., 2016). Therefore, many research groups have been working on micro scanner and several types of micro scanner have been developed (Holmström et al., 2014).

However, just few of the scanners are commercially available due to the issues of robust operation, mass-producibility, low cost, high yield, and so on. Robust operation of a micro scanner should be confirmed but its multi-physics nature prevents the reliability issue to be solved easily (Kurth et al., 2007). Micro scanners are generally driven by the electrical signal(s) and accordingly handle the input optical signal(s) through its mechanical operations. On the way of converting the driving electrical signal to the corresponding mechanical operation, different types of actuation mechanism can be utilized such as electromagnetics, thermomechanics, piezoelectricity, and electrostatics as shown in Figure 1.

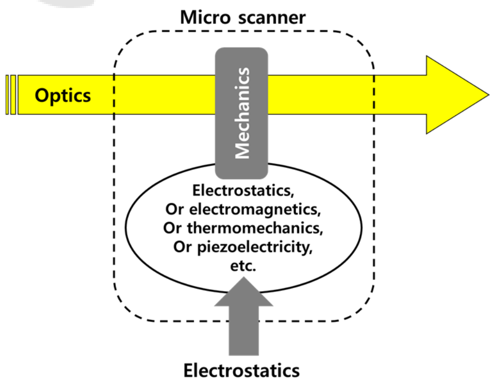

Figure 1: Multi-physics nature of a micro scanner.

In this paper, thermal stability analyses based on multi-physics simulations are presented and verified with experimental measurements. The presented

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analyses started from establishing a proper procedure on the basis of the related governing equations and completed with the experimental verifications. With the proposed procedure, we can get more information related with the thermal stability and thereafter improve the robustness of micro scanner for its successful commercialization.

2 GOVERNING EQUATIONS

Figure 2 shows the micro scanner to be analysed. It's an electromagnetically-actuated biaxial micro scanner having mechanical amplification mechanism by driven at the resonance (Cho et al., 2015).

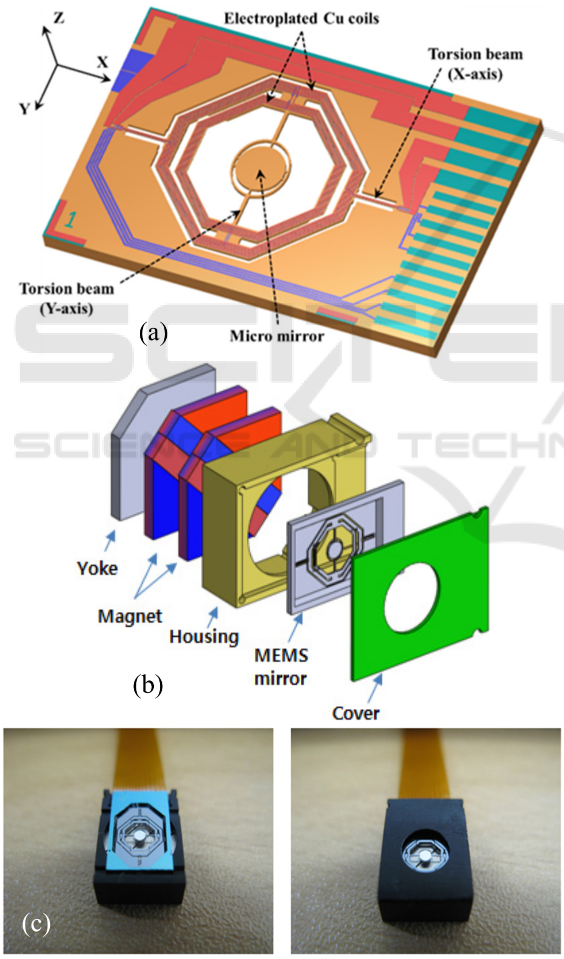

Figure 2: Electromagnetically-actuated micro scanner; (a) schematic view of the micro scanner, (b) schematic view of packaging the micro scanner, (c) the fabricated micro scanner.

When applying the driving voltage to the coils, current flowing generates electromagnetic field and therefore Lorentz force is induced through magnetic interaction with the underlying permanent magnet assembly (Magnet in Figure 2b). Torque τ caused by the induced Lorentz force acts on torsion beams as the following (Ji et al., 2007):

$$d\vec{\tau} = \vec{r} \times d\vec{F} = \vec{r} \times \left(\frac{V}{R(T)} d\vec{l} \times \vec{B} \right) \quad (1)$$

Where

- r is the radius of torsion;
- F is Lorentz force;
- V is the applied driving voltage;
- $R(T)$ is the resistance of the coil;
- l is the length of coil;
- B is the magnetic flux.

The resistance of the coil is a function of temperature T as the following:

$$R(T) = R_0[1 + \alpha(T - T_0)] \quad (2)$$

Where

- R_0 is the reference resistance at T_0;
- α is the temperature coefficient of resistance;
- T_0 is the reference temperature.

Alternatively, it can be expressed in terms of electrical conductivity σ rather than the resistance as following:

$$\sigma(T) = \sigma_0[1 + \alpha_\sigma(T - T_0)] \quad (3)$$

Where σ_0 and α_σ are reference electrical conductivity and temperature coefficient of electrical conductivity, respectively, as in the case of resistance.

The temperature of the micro scanner can be determined from the balance of thermal energy as the following (Varona *et al*, 2007):

$$\rho c \frac{\partial T}{\partial t} - k\nabla^2 T = \sigma(T)\left|\nabla V\right|^2 \quad (4)$$

Where

- ρ, c, and k are density, specific heat capacity and heat conductivity of the device, respectively;
- $\sigma(T)$ is the temperature-dependent electrical conductivity defined as Equation (3).

Added to the above energy balance equation, convective heat transfer to the surrounding given as $q=h\Delta T$ should be included as one of thermal boundary conditions, where q is the heat flux and h is the convection coefficient.

Finally, the resulting mechanical torsion angle θ

can be determined by Newton's 2nd law as the following:

$$I(T)\frac{d^2\theta}{dt^2} + C\frac{d\theta}{dt} + K(T)\theta = \tau \qquad (5)$$

Where

- *I(T)* is the moment of inertia;
- *C* is the damping coefficient;
- *K(T)* is the stiffness of torsion beams.

The stiffness of torsion beams and the moment of inertia are given as a function of temperature because thermal expansion coefficient and temperature coefficient of Young's modulus change the elastic property as well as the dimensions (Bourgeois et al., 1997). As a result, resonant frequency of the device can be varied as the temperature changes (Zhang et al., 2013).

3 THERMAL STABILITY SIMULATIONS

Due to the complexity of the above governing equations caused as they are fully coupled, commercially-available numerical tool which can handle multi-physics problem was used (CoventorWare^{TM}, 2016) following the simulation procedure shown in Figure 3. The final goal of the analyses was to get more insight related with the thermal stability of resonant frequency for the design optimization and also to set up the allowable range of the driving voltage *V*.

3.1 Parameter Definitions

In order to analyse the thermal stability of the micro scanner accurately, it's required to define all the related parameters correctly. Based on the measured resistance $R(T)$, the temperature coefficient of resistance α was calculated as 0.0086 /K. The other parameter of the electric conductivity σ is necessary but it's impossible to be analytically calculated due to the geometric complexity. Thus parametric numerical simulation on the electroplated Cu coil was required to get the best-fitted value of the conductivity. Figure 4 showed the fitted result of 1.57×10^5 S/cm. Lee et al., (2003) reported electric conductivity of the electroplated Cu as 1.59×10^5 S/cm, which matched well with the fitted result.

Another parameter of convection coefficient *h* was also fitted to the simulation results as shown in Figure 5. In order to increase the fitting accuracy, two sets of the measured temperature with 1V and 3V driving voltage, respectively, were used. The resulting *h* of 327 pW/(um^{2}K) was obtained. Experimental verification on the required simulation parameters of α, σ, and *h* guaranteed the following simulation results to be reliable.

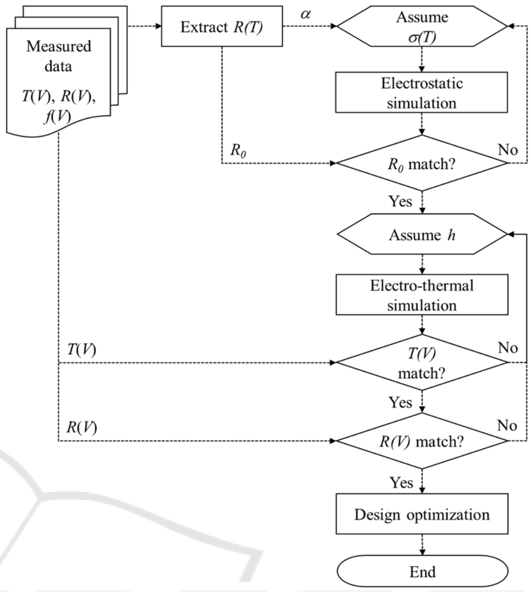

Figure 3: Flow chart related with thermal stability simulation procedures.

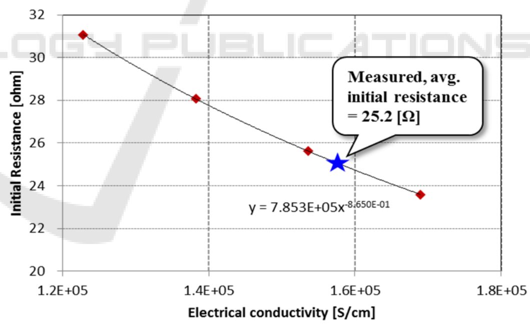

Figure 4: Fitting the electric conductivity based on the measured result.

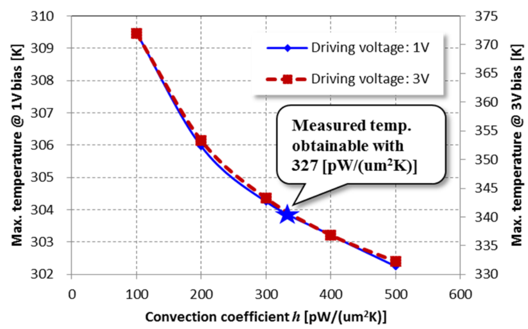

Figure 5: Determining the convection coefficient.

3.2 Simulation Results Verification

Fully-coupled electro-thermo-mechanical simulation revealed the thermal stability issue of the micro scanner. First of all, Joule heating caused by the applied bias voltage increased the device temperature as shown in Figure 6 where the simulation results matched well with the measured except the high bias region. Here the measured temperature was obtained with thermal image camera while changing the applied DC bias voltage.

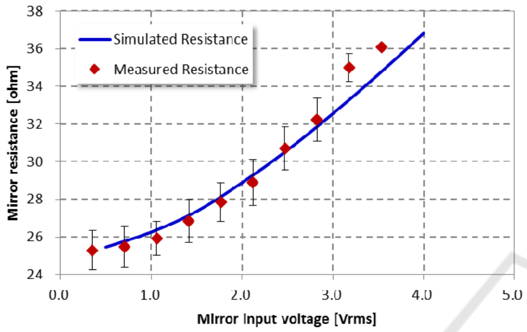

Figure 6: Verification of the temperature change as a function of the applied bias voltage.

The temperature increase changes the coil resistance and vice versa. The coil resistance and the following resonant frequency were measured with a voltage-follower circuit connected to oscilloscope, which requires AC bias voltage. Increasing the bias voltage more than 4 V_{rms} made the micro scanner operation unstable, which matched with the high bias region showing the saturated behaviour in Figure 6. Hereafter the bias voltage was limited to be lower than 4 V_{rms}. The resistance variation caused by the increased temperature were well captured by the electro-thermal simulations as summarized in Figure 7.

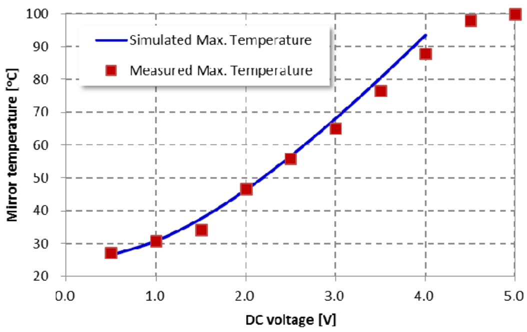

Figure 7: Verification of the resistance change as a function of the applied bias voltage.

When a constant voltage is applied, the temperature-induced increase in the coil resistance reduces the current flowing, which decreases the driving mechanical torque as described in Equation (1). Then the decreased torque causes the reduction in mirror rotation θ as shown in Equation (5). To avoid such a performance degradation, the temperature of the device should be controlled within the allowable range.

Considering the increases in temperature and resistance shown in Figure 6 and 7, respectively, the driving voltage should be limited not to exceed 4 V because severe temperature increase in the electroplated coil may damage the coil permanently.

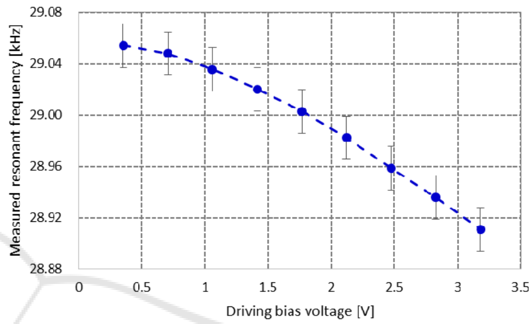

Figure 8: Measured resonant frequency shift due to the applied bias voltage.

Another important effect of the temperature increase is the resonant frequency shift as shown in Figure 8, which was caused by thermal expansions in the device geometry and Young's modulus change. As the presented micro scanner amplifies its rotation angle by driven at resonance, frequency shift means that the change of operation point and thus additional control algorithm such as phase-locked loop (PLL) is required. The resonant frequency shift is unavoidable but it should be minimized because an abrupt shift makes the controller more complex.

Related with the resonant frequency shift, it was possible to extract dominant parameters such as coil dimension, coil resistance, and heat dissipation structure based on the previous multi-physics simulations. Thus the proposed thermal stability simulation procedure can be utilized for the design optimization of the micro scanner.

4 CONCLUSIONS

In order to analyse the complex thermal stability issue of MEMS micro scanner, multi-physics simulation procedure was proposed. As the MEMS micro scanner amplifies its scanning angle by driven at resonance, it's important to maintain the resonant frequency stable although the increased device temperature caused by Joule heating would change the resonance. The proposed simulation procedure calculated the voltage-induced temperature increase accurately and revealed the dominant parameters related with the thermal stability of the micro scanner. Those results were proven by comparing to the measured experimental data. It's expected the established procedure to contribute to the successful commercialization of MEMS micro scanner by increasing its thermal stability.

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