AN ONLINE TOOL FOR SIMULATING ELECTRO-THERMO-MECHANICAL FLEXURES USING DISTRIBUTED AND LUMPED ANALYSES

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1 ABSTRACT

We present a new online tool that uses an integrated algorithm that couples distributed and lumped analyses to simulate a thermal actuator. Users demand faster results with comparable accuracy. Compared to distributed analysis alone, our integrated algorithm is faster and nearly as accurate. The tool uses distributed analysis to model the electro-thermal domain, and imports the resultant temperature into lumped analysis, which is used to model the thermo-mechanical domain. The relative errors between the results found in our integrated algorithm are about 12% and 6% to the experimental results and the results in distributed analysis, respectively. The error is likely due to the mismatch of the geometric and material properties between the true and the simulation values. Our integrated algorithm is about 10 times faster than pure distributed analysis. We present a solution to a parametric design problem by using our integrated algorithm and also present the web interface of the tool.

Keywords: finite element analysis (FEA), lumped analysis, online tool, multi-domain simulation, micro-electro-mechanical system (MEMS) design

2 INTRODUCTION

In order to accurately and rapidly capture the behavior of complicated multi-domain micro-electro-mechanical system (MEMS), it is important to understand how to leverage the advantages of different modeling methods. With the development of MEMS during the last two decades, the complexity of the system has been increased. Several commercial tools based on distributed analysis have been developed such as [1] and [2]. They are good at characterizing the details such as the distribution of temperature throughout a device. On the other hand, the tools that use lumped analysis are also crucial [3] due to their many time-saving attributes in the areas of configuration, simulation, modification, and parameterization. In this paper we integrate distributed and lumped analyses to reduce computational time while preserving accuracy.

As a test case, we model a micro-scale bent-beam thermal actuator [4], also known as a chevron actuator. The temperature of the device layer increases with electrical current. And its displacement increases with temperature. Conventionally, a designer can analyze such a device using distributed analysis [1], [5], which requires a large amount of time and memory; or lumped analysis [6], which requires the construction of equivalent circuit models for electrical, thermal, and mechanical domains.

The present integrated algorithm couples distributed analysis (COMSOL [2]) and lumped analysis (SUGAR [3]) to reduce the time of computation compared to using distributed analysis alone. The modeling parameters of the chevron actuator are parameterizable. The tool is freely available on nanoHUB [7]. This paper is organized as follows. The integrated algorithm is discussed in Section 2. The simulation results are compared against the experimental results as well as the distributed analysis results in Section 3. A design optimization application and the web interface are presented in Section 4.

3 INTEGRATED ALGORITHM

3.1 Thermal Actuator Model

The true chevron actuator [8], its exaggerated schematic, and a simulated subcomponent are shown in Fig. 1. The symmetric device comprises a central shuttle supported by a set of thermally actuated beams that are anchored to the substrate. After applying voltage at the anchors, the temperature of the device increases due to Joule heating. As the beams lengthen due to thermal expansion, the shuttle deflects in the positive y-direction. For simplicity, we focus our attention on a subcomponent of the chevron actuator, Fig. 1(c).

3.2 Integrated Algorithm

In this section we describe how we integrate the distributed and lumped analyses. We use distributed analysis to model the electro-thermal domain, and lumped analysis to model the thermo-mechanical domain.

Distributed analysis. A distributed analysis simulation of the subcomponent of the chevron actuator from Fig. 1(c) is shown in Fig. 2(b). A color-plot of a temperature distribution in Fig. 2(a) is mapped onto its surface in Fig. 2(b).

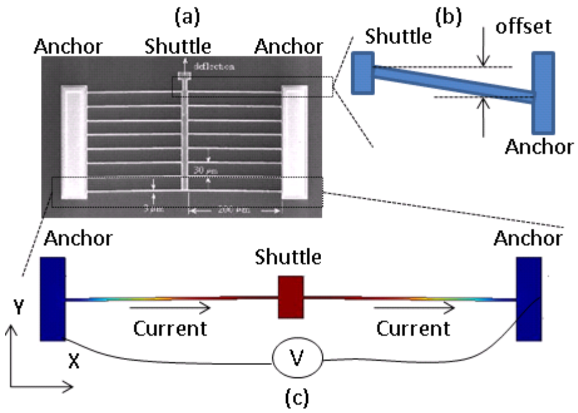

Figure 1: (a) True chevron actuator [8]; (b) Exaggerated schematic to show small offset; (c) Simulated subcomponent under investigation.

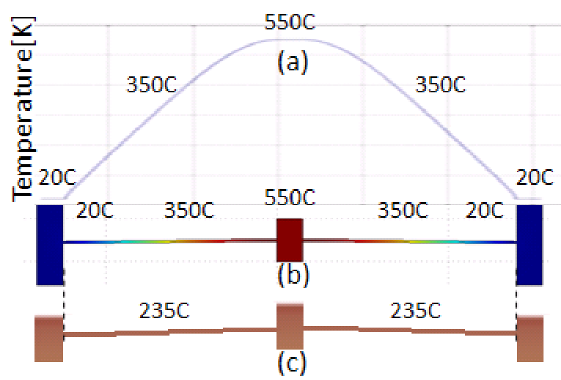

Figure 2: (a) Steady-state temperature distribution of the simulated subcomponent when input current is $1.4mA$; (b) Temperature color-plot for distributed analysis (Beam on one side is $250\mu m$ in length and $3\mu m$ in width, the middle shuttle is $30\mu m$ in length and $50\mu m$ in width, and the thickness of the device layer is $3.5\mu m$.); (c) Average temperature of the beams used in lumped analysis.

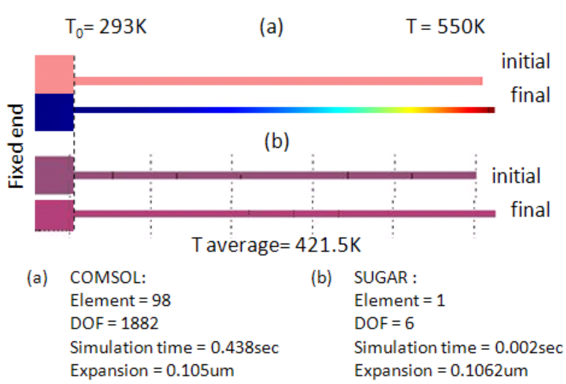

Figure 3: Cantilever thermal expansion simulated by both (a) distributed analysis and (b) lumped analysis with average temperature.

The dimension of the simulated device is given in Fig. 2. By assuming the chevron actuator is in a high vacuum ($1 \times 10^{-5} Torr$) with surrounding temperature equals to $293K$ as the experiment setup in [8], thermal conduction along the device layer, from the device layer to the substrate through the bond pads, and surface radiation are the only paths for heat transfer. The substrate is neglected in the model because the existence of silicon nitride and poly-silicon layers between the device layer and the substrate to prevent the thermal conduction. 1395 tetrahedral meshing elements are used in the distributed analysis. We keep the electro-thermal properties of the device layer the same as those listed in [8]. The density and surface emissivity equal to $2330 kg/m^3$ and 0.6, respectively. The temperature dependent resistivity ρ and thermal conductivity κ are given as [8],

$$\begin{aligned}&\rho = 3.4 \times 10^{-3}[1 + 1.25 \times 10^{-3}(T - 293)], and \\ &\kappa = [(-2.2 \times 10^{-11})T^3 + (9 \times 10^{-8})T^2 - \\ &(1 \times 10^{-5})T + 0.014]^{-1}.\end{aligned} \tag{1}$$

Lumped analysis. A lumped analysis simulation of the subcomponent of the chevron actuator from Fig. 1(c) is shown in Fig. 2(c). For lumped analysis, only node temperatures at the ends of the beams are defined. That is, instead of using a distributed temperature profile as in distributed analysis, an average temperature is used in lumped analysis because it yields nearly the same overall deflection as applying distributed temperature for linear models as shown in Fig. 3. The relative error is 1.14%. The thermo-mechanical properties of the device layer are obtained from [8]. The Young's modulus is $165GPa$, and the Poisson's ratio is 0.3. The thermal expansion coefficient is given as [8],

$$\begin{aligned}&\alpha = 10^{-6}\{3.725[1 - exp(-5.88 \times 10^{-3} \times \\ &(T - 125))] + 5.548 \times 10^{-4}T\}.\end{aligned} \tag{2}$$

The lumped analysis model only considers axial strain, because off-axial strains do not significantly contribute to the actuation. The magnitude of the equivalent external force due to thermal expansion as shown in Equ. 3 can be found based on Hooke's Law ($F = Ky$), where the axial stiffness of the beam is $K = AE/L$ and the axial expansion due to temperature increase is $y = L\alpha(T - T_0)$. Hence, the equivalent nodal force is:

$$F = AE\alpha(T - T_0) \tag{3}$$

where A is the cross sectional area of the beam, E and α are the Young's modulus and thermal expansion coefficient of the device layer. T and T_0 are the steady-state average temperature calculated in electro-thermal domain and the surrounding temperature, respectively. The force is applied at the connecting node between the

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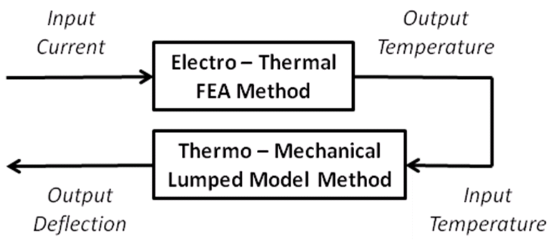

Figure 4: Process flow chart of the integrated algorithm.

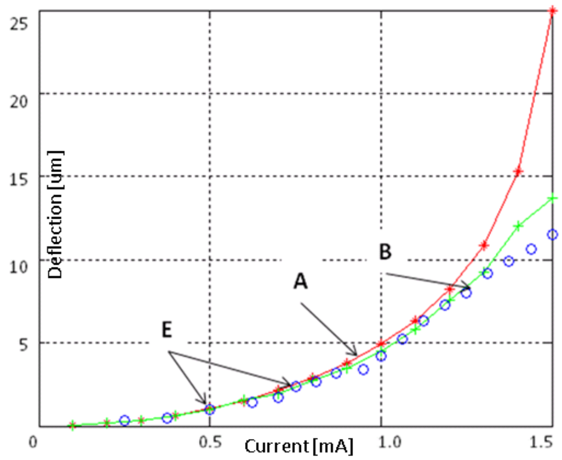

Figure 5: Results comparison among integrated algorithm (curve A), pure distributed analysis (curve B) and estimated experimental data from [8] (E).

beam and the shuttle, and the direction is along the inclined beam and pointing to the shuttle.

We outline the coupling between the distributed and lumped analyses in Fig. 4. The integrated algorithm is coded in MATLAB [9].

4 RESULT & DISCUSSION

The deflections obtained from the integrated algorithm are compared with those gained from pure distributed analysis in COMSOL as well as the experimental data from [8] in Fig. 5. The average relative error between our integrated algorithm and the experimental data is about 12% when the input current is in the range from $0.2mA$ to $1.2mA$. We find two sources of error: 1) The error in estimating the experimental data from a plot given in [8]; 2) The error in geometric and material properties between simulation and experiment. For example, we find that by increasing the Young's modulus by 10% and assuming $0.3\mu m$ over-etch during the fabrication, the average relative error drops to 4%.

The average relative error between the integrated algorithm and pure distributed analysis is about 6%. The simulation time of our integrated algorithm (147 seconds) is about 10 times faster than the pure distributed analysis (1549 seconds).

When the input current is large (more than $1.2mA$), the experimental results are much smaller than the simulation results in either one of the analyses. The possible reason of self-annealing and localized melting at the grain boundaries caused by second breakdown in poly-silicon under high temperature (about $1300°C$) is discussed in [8]. Also, for high input current, the deflections found in our integrated algorithm are much larger than those in the pure distributed analysis as shown in Fig. 5. This is because the effect of the stress in the device layer induced by the lateral deflection is not considered in the lumped analysis within the integrated algorithm. The stiffness increases with the lateral deflection so that the true device becomes stiffer than the simulated device when large deflection occurs.

5 APPLICATION

5.1 Design Parameterization

Fig. 6 shows an example in which the layer thickness and input current are parameterized to get maximum shuttle deflection while avoiding over-heating the device. The temperatures less than $600K$ generated by different combinations of current and thickness are shown in Fig. 6(a) The maximum deflection is $8.65\mu m$ with $1.2mA$ and $2.8\mu m$ for input current and layer thickness as shown in Fig. 6(b).

5.2 Web Interface of the Online Tool

The online tool that contains the lumped analysis portion of the presented algorithm is freely available on nanoHUB [7]. Computation takes place remotely on nanoHUB clusters. We created the web interface shown in Fig. 7 with the RAPPTURE Toolkit [10]. RAPPTURE is used to prevent users from having unfettered access to MATLAB, which is commercially available only. Although the COMSOL engine was used in the presented effort, the electro-thermal portion of the tool is not publicly available online as of yet. We are expecting to incorporate a freely available distributed analysis tool. However, the algorithm as presented requires access to COMSOL.

Static analysis and one- or two-parameter sweep analyses can be performed. All parameters can be assigned and selected by users to do sweep analyses.

6 CONCLUSION

A new integrated algorithm which couples distributed and lumped analyses has been presented. A chevron thermal actuator has been simulated within electro-thermo-mechanical domain. The results of the integrated algorithm have been compared to experimental data in [8], and the average relative error is about 12% when the

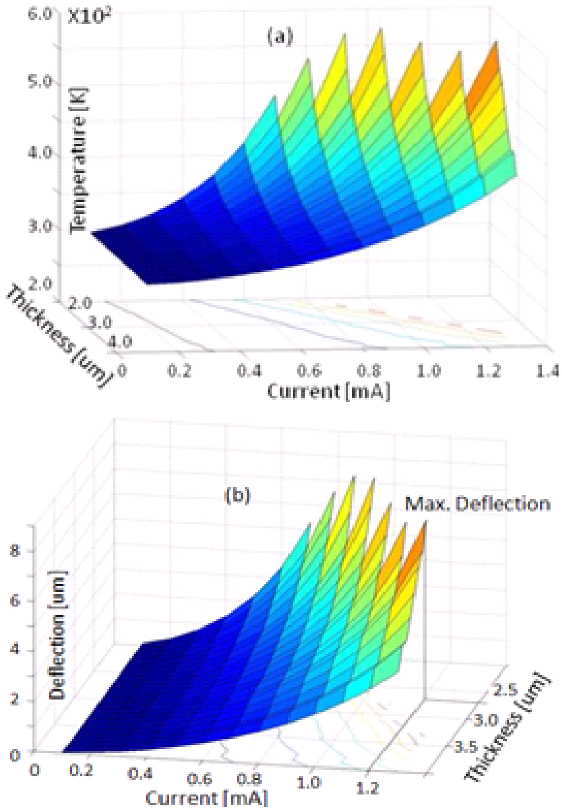

Figure 6: Two parameter sweeps: (a) shows the temperatures less than $600K$ generated by different combinations of current and thickness; (b) shows the maximum deflection is $8.65\mu m$ among the combinations found in (a).

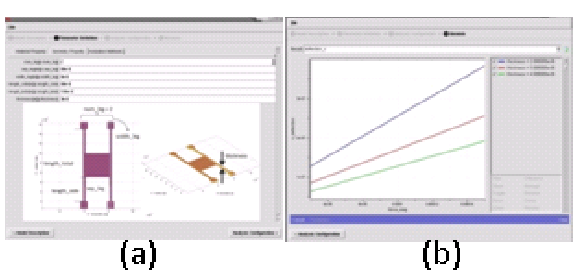

Figure 7: Screenshots of the online tool. (a) Geometric parameter input for chevron actuator; (b) Output plot of 2-parameter sweep analysis.

input current ranges from $0.2mA$ to $1.2mA$. The integrated algorithm has been compared to pure distributed analysis. The average relative error is about 6%, and the simulation time of the integrated algorithm is about 10 times faster. We believe that geometric and material property mismatches are responsible for the error between simulation and experiment. We have found that the accuracy of our integrated algorithm decreases with the increase of the lateral deflection.

The algorithm has been used to quickly and fairly accurately explore a design space. And an online tool based on this algorithm has been developed on nanoHUB.

REFERENCES

[1] Coventor, Inc., 4000 CentreGreen Way, Suite 190, Cary, NC, USA, 27513. [Online]. Available: http://www.coventor.com/

[2] COMSOL, Inc., 1 New England Executive Park, Suite 350, Burlington, MA, USA, 01803. [Online]. Available: http://www.comsol.com/

[3] J. Clark and K. Pister, "Modeling, simulation, and verification of an advanced micromirror using sugar," *Microelectromechanical Systems, Journal of*, vol. 16, no. 6, pp. 1524–1536, 2007.

[4] L. Gianchandani, Y. Inc, and C. Campbell, "Bent-beam electrothermal actuators-Part I: Single beam and cascadeddevices," *Microelectromechanical Systems, Journal of*, vol. 10, no. 2, pp. 247–254, 2001.

[5] N. Mankame and G. Ananthasuresh, "Comprehensive thermal modelling and characterization of an electro-thermal-compliant microactuator," *Journal of Micromechanics and Microengineering*, vol. 11, no. 5, pp. 452–462, 2001.

[6] R. Li, Q. Huang, and W. Li, "A nodal analysis method for simulating the behavior of electrothermal microactuators," *Microsystem Technologies*, vol. 14, no. 1, pp. 119–129, 2008.

[7] Network for Computational nanotechnology, 1205 W. State Street, West Lafayette, IN, USA, 47906. [Online]. Available: http://www.nanohub.org/

[8] C. Lott, T. McLain, J. Harb, and L. Howell, "Modeling the thermal behavior of a surface-micromachined linear-displacement thermomechanical microactuator," *Sensors & Actuators: A. Physical*, vol. 101, no. 1-2, pp. 239–250, 2002.

[9] I. The MathWorks, 3 Apple Hill Drive, Natick, MA, USA, 01760. [Online]. Available: http://www.mathworks.com/

[10] M. McLennan, "The rappture toolkit." [Online]. Available: http://rappture.org/

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