Feasibility Study of Thermal Actuators for MEMS Variable Emittance Radiators Using COMSOL Multiphysics

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Abstract: A COMSOL Multiphysics®-based analysis of an innovative thermal actuation system capable of overtaking the traditional electrostatic comb drive, nowadays used for actuating the shutter array of variable emittance radiators, has been conducted as to validate this technology for the future active thermal control of CubeSats operating in an harsh environment, where thermal actuators overtakes comb drives due to their higher radiation hardness. Actuators based on electrostatic forces operate at low power and high frequency, and are highly desirable. However, they have typically small deflections and require either close dimensional tolerance or high voltage to achieve large deflections. On the other hand, actuators based on thermal expansion effect can provide a large force and a deflection perpendicular or parallel to the substrate. They have been shown to be a valuable complement to electrostatic actuators. In particular, polysilicon thermal actuators can operate in an integrated circuit (IC) current/voltage regime and may be fabricated by a surface–micromachining technology that is compatible with IC technology.

Keywords: CubeSats, Thermal Control, Radiators, Variable emittance, Thermal Actuators.

1. Introduction

Miniaturization in space is becoming nowadays an increasing trend that will take over traditional big satellite missions. As a consequence, MEMS are used in a lot of S/C subsystems to decrease the mass budget of CubeSats together with a decrease in size. Above all, Active Thermal Control of CubeSats has become critical due to the increase in payload complexity and the need to extend miniaturized satellites beyond Earth's Orbit, even where the solar proximity might become a challenge for the thermal subsystem. In particular, active control requires too much power (e.g. heaters), which is counter-trend, or additional mass, sometimes with movable parts and/or huge radiators that are unwanted. Studies have been made to come up with a smart miniaturized thermal control, that avoids mass and power demands while still being able to eject wasted heat from electronics in an active and controlled way. Based on these considerations, NASA flew the ST-5 mission to validate innovative MEMS technology in the Thermal Subsystems, that comprised two different types of radiator designs: a louver design, which is more like the traditional vane louvre, and a shutter design (Fig. 1), in which the shutter slides laterally instead of opening outward [6].

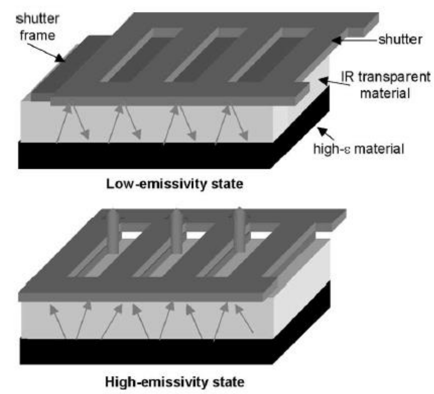

Figure 1: Illustration of shutter concept. In the low emissivity state, the shutter frame and shutter block the light emitted by the high-substrate backing from escaping the structure. In the high-emissivity state, the shutter is moved to allow light to escape [10].

For both these two designs, the temperature of the radiator can be approximated as ([6]):

$$T_R(t) = T_0 + (T_\infty - T_0)[1\text{-}e^{-\frac{k+4A\epsilon\sigma T_0^3}{C_t}t}] \qquad (1)$$

where T_∞ is the steady-state temperature, T_0 is the satellite temperature, k is the thermal conductance, A is the radiator area and C_t is the thermal capacitance. Any terms representative of an external power from an heater are absent, and the radiator temperature changes only depending on the values assumed by ϵ. Since the shutter design is characterized by a higher robustness with respect to the louvre design, the former has been chosen for this feasibility study.

Figure 2 shows an optical microscope image of the assembly: $\Delta\epsilon$ is here provided by the high (bare silicon) and by the low emissivity (gold-coated) substrate.

The actuation system is here shown in the upper-left part. Since the design was validated during the ST-5 mission, this system still uses standard MEMS comb drives with relatively high driving voltages (tens of volts) necessary. A reasonable improvement thus seems a concept in which a high-force, low-voltage actuation system is guaranteed.

Thermal actuators seem to be an option to consider, due to the relatively high displacement they can provide with very low voltages applied. Moreover, they are less radiation-sensitive with respect to their electrostatic counterpart, and so they might become a valid alternative to actual comb drives for future interplanetary swarm explorations, in which the radiation environment is high compared to Earth's orbits, and represent a challenge for electrostatic devices.

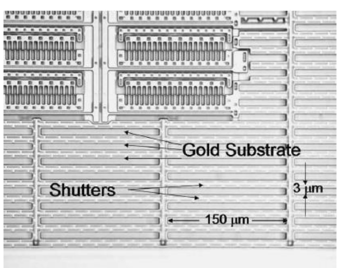

Figure 2: High-resolution optical microscope image of the motors and shutters [6].

Even if a lot of research has been done in design, analysis and application of MEMS thermal actuators, there is less work done in the modeling and optimization of thermal actuators. Furthermore, nothing has ever been investigated in the potential applications of such devices in the actuation mechanism of a shutter array like the one described above, as comb drives have always been considered as the main solution. However, in order to produce the same force as the thermal actuators, comb drive devices requires a much larger footprint and higher Voltages, and there might be the need to validate thermal actuation systems in order to assess whether or not such a system is able to displace the shutter of the exact amount needed to optimize the required change in emissivity, and overtake actual comb drive devices.

2. Model Definition

According to the problem statement, a required displacement is used as an objective to analyze and optimize a thermal actuator for the mentioned specific application. In order to do so, two different models have been built in COMSOL as to decouple some physical aspects of the problem and improve every single analysis by means of separated studies:

1. a simplified 3D Structural Model of the shutter array was built, in order to calculate an estimate of the stiffness of the device that need to be counteracted by the actuation system (Fig. 3).

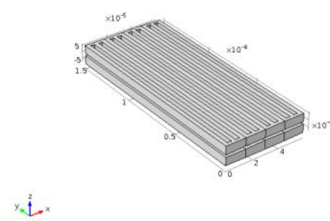

Figure 3: 3D model of the shutter array

2. A 3D Multiphysics model of a U-shape Thermal Actuator was created, to check the feasibility of this technology with respect to electrostatic actuators in terms of required voltage and output tip displacement (Fig. 4).

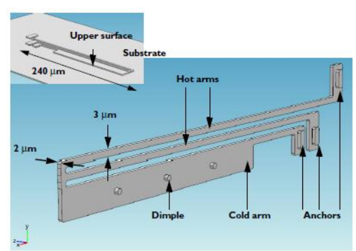

Figure 4: Geometry of the Thermal Actuator.

2.1 Thermal Actuator

The selected model consists of a two-hot-arm thermal actuator made of polysilicon. The actuator is activated through thermal expansion.

The temperature increase required to deform the two hot arms, and thus displace the actuator, is obtained through Joule heating. The greater expansion of the hot-arms, compared to the cold arm, then causes a bending of the actuator and returns the desired tip displacement.
As explained before, the actuator operates on the basis of thermal expansion generated by non-uniform Joule heating. According to [1], non-uniform heat may be produced either by using different materials with different coefficient of thermal expansion or by using two or more beams of the same material but different cross-sections. The thermal actuator has been designed as shown in Fig. 4. The actuator includes a cold harm, separated by a gap from two hot harms, the latter being characterized by a higher electrical resistance and thus by a higher Joule heating with respect to the former one. The whole device is then constrained on one face, thus the resulting thermal expansion will lead to a deflection, and a mechanical force will finally develop.
The geometrical values have been taken from [4] and are listed in Table 1.

2.2 3D Shutter Array

The simplified 3D model of the shutter shown in Fig. 3, representative of the array the actuator shall actuate, has been built in COMSOL, in order to compute the stiffness of the device. Since we are only interested in the dynamics of the shutter, and not in the radiation performance, it was decided to decouple the Heat radiation and Solid Mechanics and calculate the stiffness only.

3. Governing Equations and Boundary Conditions

To be compatible with IC technologies, constraints in terms of allowed materials need to be taken into account. Indeed, since poly-silicon is the driving material for such technologies, it was chosen as the material to meet IC technology requirements.
Table 2 list the main properties of the selected material that have been used during the analysis. Also, the melting temperature for the selected material has been found to be T_{melt}= 1123.15 K.

Name	Value (µm)	Description
d	3	Height of the hot arm
d_w	15	Height of the cold arm
gap	3	Gap between arms
wb	10	Width of the base
wv	50	Length difference between hot arms
L	240	Actuator length
L1	L-wb	Length of longest hot arm
L2	L-wb-wv	Length of shortest hot arm
L3	L-2wb-wv-L/48-L/6	Length of cold arm, thick part
L4	L/6	Length of cold arm, thin part

Table 1: Thermal Actuator Global Parameters [4].

Since the material properties of polysilicon are temperature dependent, the involved physics phenomena described above are fully coupled. The electric current through the hot arms, generated by the applied Voltage, increases the temperature in the actuator, which in turn causes thermal expansion and changes the electrical conductivity of the material as the resistance R = $\frac{\rho l}{S}$ of the hot and cold arms differs. The steady-state simulation of the device entails the sequential solution of three sets of differential equations that govern the electric current, thermal, and thermo-elastic behaviors [7]:

1. The current distribution in the structure for specified voltage boundary conditions is determined by solving the following equation for continuity of current:

$$\nabla \cdot \mathbf{J} + \boldsymbol{i_v} = 0 \qquad (2)$$

where $\boldsymbol{i_v}$ is the current source per unit volume (absent in our analysis), $\mathbf{J} = \frac{1}{\rho}\boldsymbol{E}$ is the conduction current density vector, and $\mathbf{E}$ is the electric field associated to the potential that has been applied as a boundary condition.

Property	Symbol	Value	Unit
Coefficient of Thermal Expansion	α	2.6	1/K
Heat Capacity at constant pressure	c_p	678	J/(Kg K)
Relative Permittivity	ϵ_r	4.5	-
Density	ρ	2320	Kg/m^3
Thermal Conductivity	k	34	W/(mK)
Electrical Conductivity	σ	50	kS/m
Young's Modulus	E	160	GPa
Poisson's Ratio	ν	0.22	-

Table 2: Material Properties - Poly Silicon [5].

2. After obtaining the current distribution, non-uniform Joule heating is computed as $\dot{q}= \rho|\mathbf{J}|^2$. Then, the following steady-state heat conduction equation is solved for temperature distribution for specified thermal boundary conditions on temperature and heat flux (including insulation, natural convection, and radiation):

$$k\nabla^2 T + \dot{q} = 0 \quad (3)$$

3. The third and final step in the simulation is to solve the elastic equilibrium equations under temperature induced thermal strain:

$$\nabla \boldsymbol{\sigma} = 0 \quad (4)$$

with:

- $\boldsymbol{\sigma} = D(\boldsymbol{\epsilon} - \boldsymbol{\epsilon_t})$ being the stress
- D being elasticity tensor that relates stress and strain
- $\boldsymbol{\epsilon_t}$ being the thermal strain; for plane-stress conditions: $\boldsymbol{\epsilon_t} = [\alpha(T - T_0); \alpha(T - T_0); 0]$
- T_0 reference temperature.

The segregated approach, which solves each physics sequentially until convergence, is the automatic solver used by COMSOL for an analysis that involves Electric Current, Thermal Expansion, and Mechanical Displacement, and is preferred to the Fully Coupled approach, as each of the physics can use the optimal solver.

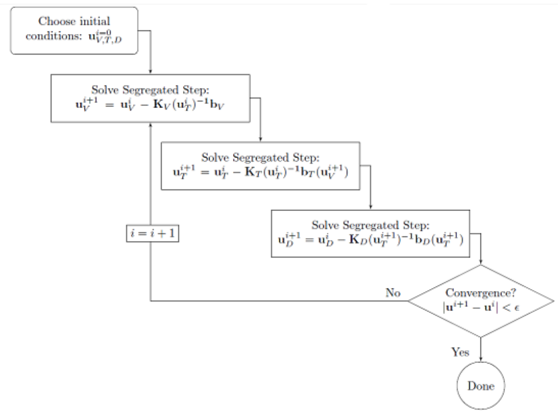

Figure 5: Segregated Step Approach [5].

Figure 5 shows the procedure followed by COMSOL in the segregated mode. However, according to [5], although the thermal strain and the Young's Modulus are dependent upon temperature, the voltage and temperature solutions do not depend upon the displacements or stresses. That is, there is a uni-directional coupling from the thermal problem to the structural problem. It can thus immediately see that there is an even more efficient way to solve this problem: the voltage and temperature problem can be solved first, and subsequently COMSOL can solve for the output displacements.
Figure 6 shows this procedure. What has been found is that, by splitting the Steady State Analysis into the above-mentioned two steps, the computational time can be reduced, thus potentially helping the optimization study that will be performed.

4. Model Validation

4.1 Thermal Actuator

Before considering the shutter stiffness, a parametric study of the thermal actuator has been made, both to check if the model agrees with analytical results and to assess if the output displacement is reasonably close to the required displacement of 3µm, before proceeding with an optimization study.
Simulations have shown that, with reasonably low voltages, displacement close to the requirement are possible.

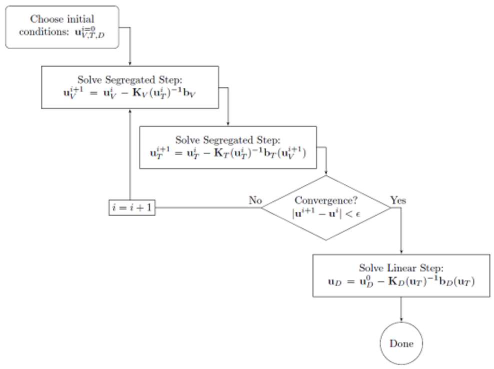

Figure 6: Segregated Improved Step Approach [4].

Furthermore, the model is validated in terms of temperature distribution, since the maximum temperature occurs in the middle of the actuator according to what has been discovered in [2],[3]). The tip displacement that results is then given by the following relation (see Fig. 7):

$$\Delta x = L\sqrt{2\alpha\frac{V^2 d * gap}{\rho L(d_w - d)\lambda}} \tag{5}$$

where V is the applied DC voltage, λ the thermal conductivity, α the thermal expansion coefficient, and ρ the resistivity of the material we adopted.
What results is that the simulated displacement, δ_S= 2.54μm, is comparable to the theoretical one, δ_t = 2.11μm, found by filling the above equation. The variation is probably due to geometrical simplifications done in [8],

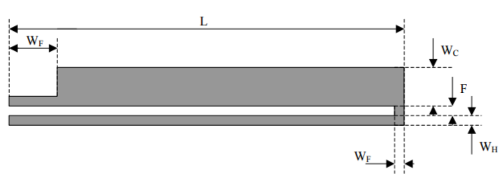

Figure 7: Geometry used for model validation [13]

together with the difference in having one (theoretical model) and two (COMSOL model) hot harms. It can be assumed that the model is validated by analytical calculations.

4.1 3D Shutter Array

To take stiffness into account, a spring-like force has been inserted in the model. At this point, a stiffness analysis was performed as to calculate an estimate of the shutter stiffness and use this value for the spring constant k.
Different forces have been applied, as to check whether the stiffness of the device changes.
Once verifying that the shutter follows an elastic behavior, the estimated stiffness was then inserted in the thermal actuator model, and the voltage varied to check the tip displacement the actuator is capable of providing, when an elastic counter-force is also applied to it.
The results in Fig. show not only that high voltages are required to have reasonable displacement, but also that the actuator is not working properly, since the maximum displacement is concentrated in the center instead of in the tip as expected.
As to overcome this problem, smaller geometries were checked for the shutter array, and different values of the stiffness have been provided to the thermal actuator model, as to perform a sweep analysis where voltage and stiffness are varied to have an idea of the actuator performance. Values higher than 10^9 N/m^3 were found to lead to issues.

5. Optimization Study

In order to perform a good optimization, an accurate selection of the algorithm COMSOL will use need to be made first. Fig.A.10 was used as a useful indication of which optimization solver to use, based on the specific study problem the optimization is aiming to solve.
Since a change in geometry has to be considered, a re-mesh is needed. Furthermore, as the melting temperature of the device is a constraint that need to be taken into account, the choice need to be constrained to either the Nelder-Mead or the COBYLA algorithms. The former Nelder-Mead was finally selected.
Only a variation in total length L has been considered for the Optimization study, together with a variation in the gap between the hot and cold harms. Indeed, according to [1], these two values are highly affecting the tip displacement.
The sweep analysis confirmed that the displacement is increasing with total length L, and that temperature is not highly dependent on geometrical variations. An initial rough optimization has been done as to check the

convergence and the validity of the problem. The problem statement included:

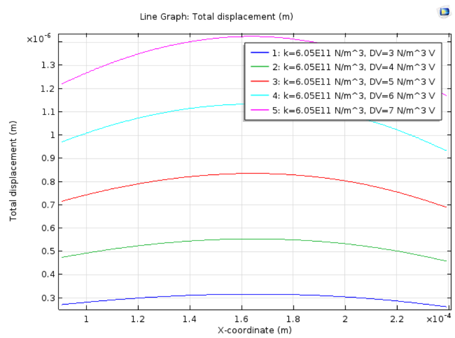

Figure 8: Total displacement of the actuator with high shutter stiffness. The highest displacement occurs in the middle of the hot arm, making the device not operating in the desired mode where the displacement is concentrated at the tip.

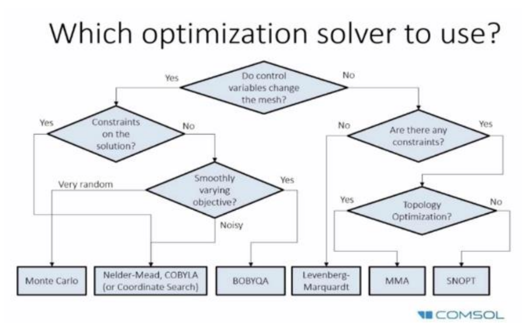

Figure 9: Optimization algorithm Tree

1. Definition of the Objective Function:

'Minimize the difference between the calculated displacement and the 3μm required value'.

2. Definition of the Control Variables: Length L, Voltage V.

3. Superposition of the Constraints:

'The Temperature shall not exceed the melting temperature of poly-silicon'.

Figures 10 and 11 show that, with a voltage of 2.7 V applied, the single thermal actuator can actuate a shutter array of stiffness k = 10^9 N/m^3 with a displacement δ_S= 2.98μm that is closed to the requirement of 3μm. Furthermore, the maximum temperature reached by the device is well below the melting temperature of Silicon.

4.1 Final Optimization and Results

As confirmed by the former optimization that was performed, a value of the displacement close enough to the required one can be achieved, validating the radiation performance requirement. However, an improved optimization might be required if an additional decrease of the applied voltage is wanted. By varying more than one dimension, indeed, lower values of the voltage can be found without losing in terms of displacement, potentially saving a few Volts that are critical for CubeSats applications in which power demand is limited. As to further optimize the device, and referring to previous observations, it has thus been decided to consider 1) more than one objective variable, as to optimize the displacement as well as minimizing the applied voltage, and 2) the gap as an additional control variable, as to allow more options for the voltage to be reduced.
The results are reflecting a good optimization, since the displacement has been further improved with respect to the previous analysis by reducing the potential down to more or less 2.5 V. Table 3 lists the final values together with the optimal parameters.
Even if the optimization results are relatively close to the one found by simply performing a sweep analysis, it has to be taken into account that, in terms of power saving, even 0.2 might be enough, and in trend with the actual attempts of reducing the voltage at the minimum level possible. Note also the decrease in the applied voltage compared to the electrostatic comb drives.

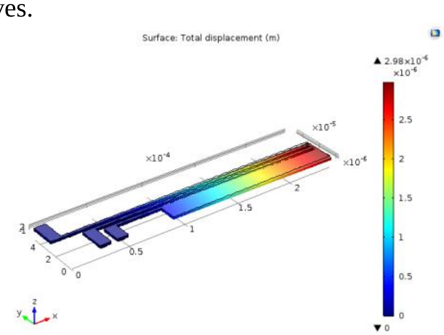

Figure 8: 1st Optimization Maximum Temperature with a prescribed array stiffness of $\mathbf{10^9}$ **N/$\boldsymbol{m^3}$**

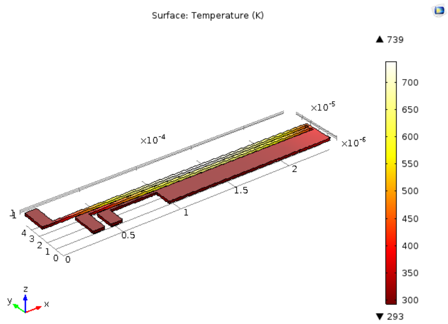

Figure 9: 1st Optimization displacement with a prescribed array stiffness of $\mathbf{10^9}$ **N/$\boldsymbol{m^3}$**

	Displacement (µm)	Voltage (V)
Parametric Study	2.54	< 3
1st Optimization	2.98	2.7
Final Optimization	3.01	2.5
Electrostatic Comb Drive	-	22-35

Table 3: Applied Voltage and Tip Displacement results compared with low-voltage electrostatic comb drives

8. Conclusions

An optimization study of a thermal actuator has been set in COMSOL Multiphysics® by varying the geometry and the applied voltage, and a tip displacement that almost coincide with the displacement required to optimize the performance of a shutter array, used to vary the emittance of a MEMS radiator, has been found. The applied voltage required by the thermal actuator turned out to be considerably low, especially when compared to electrostatic comb drives, satisfying the actual need to reduce power in CubeSats applications.
The simulation has shown that, with a single thermal actuator, only the shutter array of a geometry-limited radiator can be controlled. Indeed, a constraint has been superimpose in terms of the stiffness k, and for big scale applications, where the array is as big as shown in Fig. 1, more than one thermal actuator will be needed as to return the same displacement with an increased, combined force. Moreover, nothing has been said about the distribution mechanism that eventually transmits the displacement from the actuator to the shutter array. However, the feasibility of thermal actuators for thermal control applications has been proved, and the results obtained with the present study increase our knowledge about optimized thermal actuators.

9. References

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