

MEMS Simulations for Experimentation

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Abstract

Micro-electro-mechanical-systems (MEMS) are devices that allow systems of electronics and sensors to be placed together into very small packets of space, making them invaluable as research tools to scientists worldwide. In this work, a specific MEMS device, developed to study thin films of superfluids ^3He and ^4He , is described and studied through computer simulation using COMSOL. The MEMS device, using comb-shaped electrodes and an alternating current to create resonance in the structure, seems to bend away from the electrodes in an unexpected manner when simulated. This could cause problems when extrapolating length measurements from capacitance values between electrodes, but it can be accounted for.

I. Introduction

Micro-electro-mechanical-systems (MEMS) are micro-scale systems of integrated electronics, sensors, and actuators. MEMS are being developed to improve functionality and capabilities of technology and have already been implemented in many technologies today, such as accelerometers for air bag deployment in vehicles and as micro-nozzles in inkjet printers. MEMS are not only being used commercially but also play a significant role in scientific research. The combination of electronics and sensors, coupled with their small size, allows for the study of properties of materials and systems that before were untestable.

The goal of my research as a participant in the University of Florida's REU program and as a member of Dr. Yoonseok Lee's lab group is to simulate a MEMS device designed to investigate quasi-two dimensional superfluid ^3He and ^4He films. This novel technique has never been used in an ultra low temperature environment. To better understand the performance of the device, we have conducted computer simulations using the commercially available software COMSOL.

The MEMS device used for our simulation has two functional layers: the fixed layer and the moving layer. The fixed layer is comprised of a silicon-nitride substrate ($0.6\ \mu\text{m}$ thick) with a poly-silicon plate on top of it ($0.5\ \mu\text{m}$ thick). The moving layer, positioned above the fixed layer, is made of another poly-silicon plate ($2\ \mu\text{m}$ thick), on the opposite sides of which two comb-shaped electrodes are fabricated to form two sets of capacitors with complimenting comb-shaped electrodes ($2\ \mu\text{m}$ thick) fixed to the substrate. This top plate is suspended by four serpentine springs anchored to the substrate (see Figures 1 and 2). [1]

The MEMS Device

MEMS Specifications

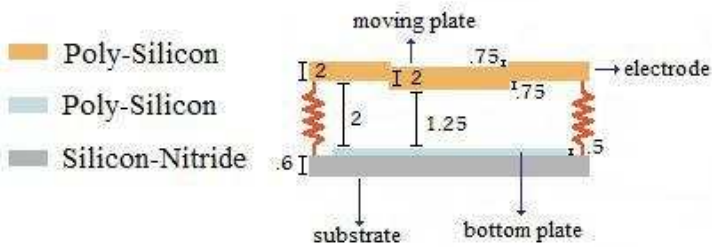


Figure 1: Side view of the MEMS device illustrating material composition and dimensions in μm .

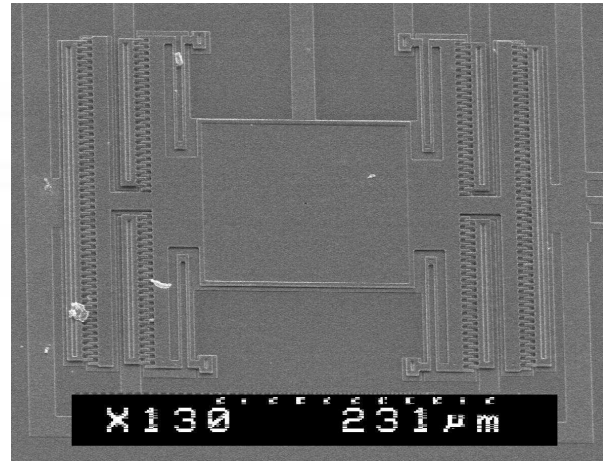


Figure 2: SEM image of the MEMS device.

The top plate oscillates when an ac voltage bias is applied to one of the fixed electrodes relative to the movable electrodes. This creates a change in capacitance between the comb-shaped electrodes due to the displacement of the movable plate. The electrodes are comb-shaped to increase the surface area of the electrode, thus increasing the capacitance between them. Increasing capacitance is crucial when dealing with MEMS devices because the devices are small, and so generate small signals. It is important to note that the bottom poly-silicon plate and the top plate are maintained at the same potential while the substrate is grounded to prevent out-of-plane motion. [2]

To test the film properties of superfluid ^3He and ^4He , the MEMS device is submerged in a pressurized test cell filled with liquid ^3He or ^4He , which is then cooled below the superfluid phase transition. The film properties of the superfluid can then be probed by measuring the damping effects on the MEMS device.

The purpose of this work is to assure that the MEMS device used in this experiment is calibrated correctly and to check for any unforeseen effects. Calibrating the system is important to have quantitative understanding of the system.

II. Simulations

In order to simulate the performance of a MEMS device, it was essential to learn how to operate a program that simulates physical models. The program used to simulate this device, COMSOL, is a robust multi-physics simulation computing software package. The first step in modeling a device is to build the geometry of the structure that one wishes to model. Initially, a structure was created using this program to exactly model the MEMS device (Geometry 1) (see Figure 3). However, there were unforeseen problems in making the model too precise. These issues began to arise as the final elements of the geometry were being assembled. When it came time to mesh the geometry, the computer ran out of memory.

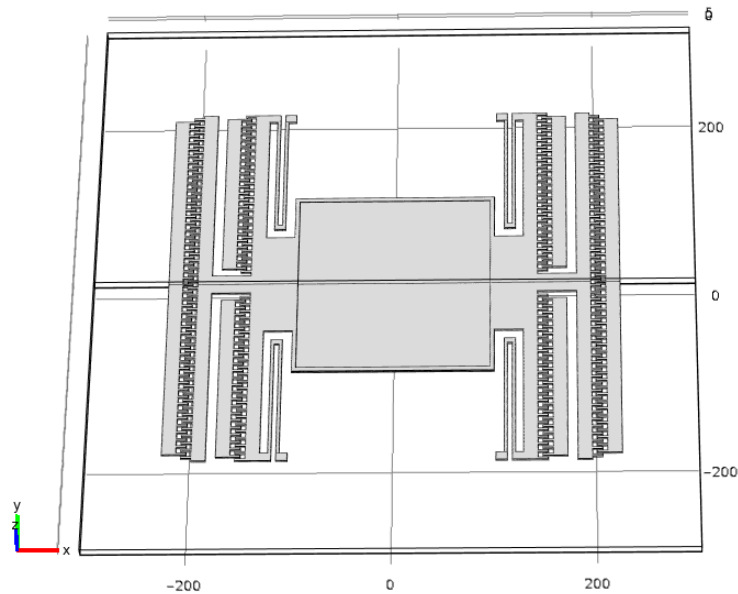


Figure 3: Geometry I: The most accurate geometry created for this study. Modeled all points of the original MEMS exactly but was consequently too memory intensive to perform any simulations.

In an attempt to solve this issue, we created extra virtual memory (since the computer hardware does not accept extra physical memory). However, this too was too memory intensive for our computer, and so we resolved to split our geometry. In this new geometry we only simulated for half of the MEMS device (Geometry 2). COMSOL allows for this by making available symmetry boundaries to add to the model. This lets the program understand that there is another component symmetric in both geometry and physical parameters. Simulation of this new model took two days to generate one viable data set. Not wanting to spend that amount of time for a single simulation to run, we resorted to creating a simpler geometry. This time, the change was the removal of the substrate. After taking preliminary checks, it was determined that the removal of this substrate would not alter the simulations greatly. Along with the the substrate, the beveled edge atop the moving plate was also removed. Removing this beveled edge resulted in no perceivable change in simulations (Geometry 3).

To completely model our device, we created two models simulating different situations. One was the MEMS device in air, at room temperature and pressure, simulating the calibration and preliminary data checks of the experiment the MEMS will be undergoing. The other model was the MEMS device in liquid helium at corresponding temperatures and pressures, simulating the initial phase of the experiment. To completely simulate the MEMS device in air, three physics nodes are needed: the electric currents, the solid mechanics, and the moving mesh packages.

The electric currents node is needed to apply the alternating voltage across the MEMS device which will then allow the MEMS to have a harmonic oscillation. Unfortunately, due to a licensing error currently being handled with the COMSOL retailers, I was unable to use the electric currents node. Instead, I resorted to the electrostatics physics node adding a direct current

to the electrodes on one side of the MEMS device. The electrostatics node solves for electric potential using the selected constitutive relation $D = \epsilon_0 \epsilon_r E$, where D is electric displacement, ϵ_0 is the permittivity of free space, ϵ_r is relative permittivity, and E stands for the total energy of the electric field [3,4].

The solid mechanics physics node is needed to apply the physical properties of the MEMS device to the geometry, such as the density, Young's modulus, and Poisson's ratio of the materials used. This node also allows for the application of fixed and moving constraints, along with applied forces. The bottom plate and fixed electrodes were set to be permanent fixed structures while the moving plate and attached electrodes were defined to have the forces of the electrostatics node affecting it. The solid mechanics node solves for movement and stresses applied to the model [4].

The last node needed for the air phase model is the moving mesh node. This node allows for the model to move in three-dimensional space and is necessary in order for COMSOL to recalculate the electrostatic force between the two combs as they move together [4]. Without it, the program would not recognize that the forces between the two comb electrodes change as they move closer together.

The second model, or the liquid helium model, is not entirely different from the air model. The main difference between this model and the air model is the changing of properties of the boundary layer around the MEMS to match those of liquid ^3He or ^4He , and the addition of a fluid physics node. The liquid helium model simulation, however, has yet to be completed.

III. Results

Of most concern to our research is the movement of the MEMS device under controlled conditions. Figures 4 and 5 show the displacement of the MEMS device, as calculated on Geometry 2, when 0.5 V is applied to the left fixed electrodes. Figure 4 illustrates the movement in the z-direction of Geometry 2 in the air phase testing simulation, while Figure 5 illustrates the movement in the x-direction. Because of the time taken for this simulation, only one potential voltage measure was recorded. Data for the displacement in the y-direction were left out because the MEMS device has no appreciable movement in that direction.

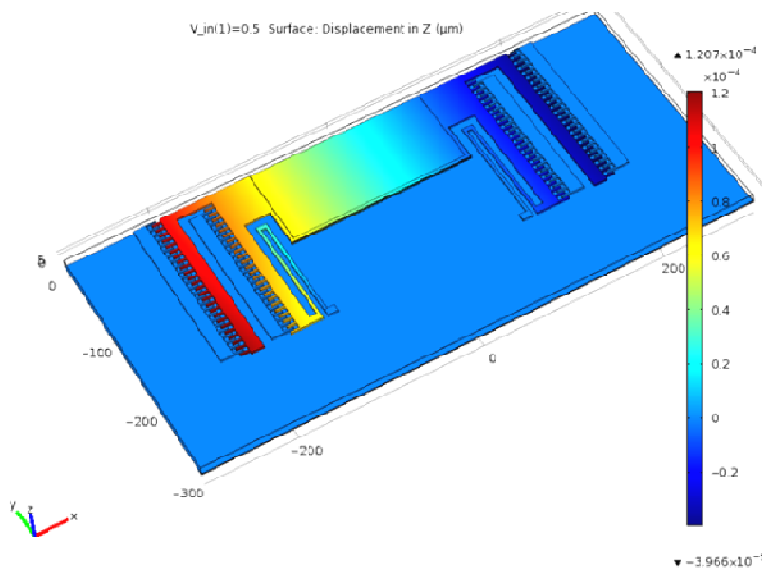


Figure 4: Displays displacement of the simulated MEMS along the z-planes for an applied electrostatic potential of .5V on Geometry 2.

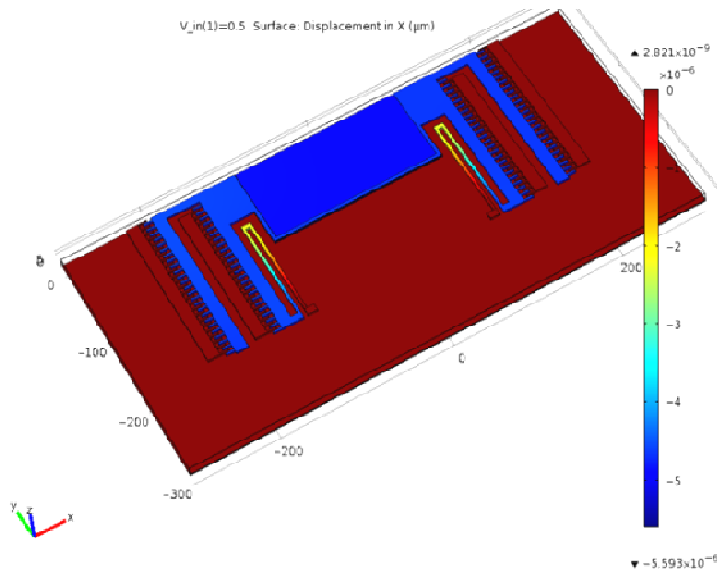


Figure 5: Displays displacement of the simulated MEMS along the x-plane for an applied electrostatic potential of .5V on Geometry 2.

The movement in the z-direction is, on average, larger than that of the x-direction by one order of magnitude. This was an unforeseen result. Movement along the z-axis is unwanted; it is the x-displacement that we want to capitalize on. The design of this MEMS is meant to be able to find a change in capacitance between the comb electrodes. The physical interpretation of capacitance is inversely proportional to the distance between the electrodes [3], so using the capacitance reading of our MEMS device we can calculate this distance. Extrapolating this distance when the only displacement is known to be in the x-plane is a simple matter, but when other planner displacements effect our system the matter becomes nontrivial .

Figures 6 and 7 are the results for the air simulation using the simplified geometry (Geometry 3) with a 0.5 V potential applied to the models left set of fixed comb electrodes. More data points were taken using this geometry, and the progression of the displacements can be seen

in Figures 8 and 9. For Figure 8, the four different lines correspond to the four moving comb electrodes, with dark blue being the electrode farthest to the left, then moving from left to right, green, red and light blue. Though this simulation is not as accurate as Geometry 2, it confirms the dilemma previously found: that the displacement of the the MEMS device along the z-plane is far greater than that of the x-plane. This simulation shows that the disparity between these two values increases proportionally as the electric potential increases.

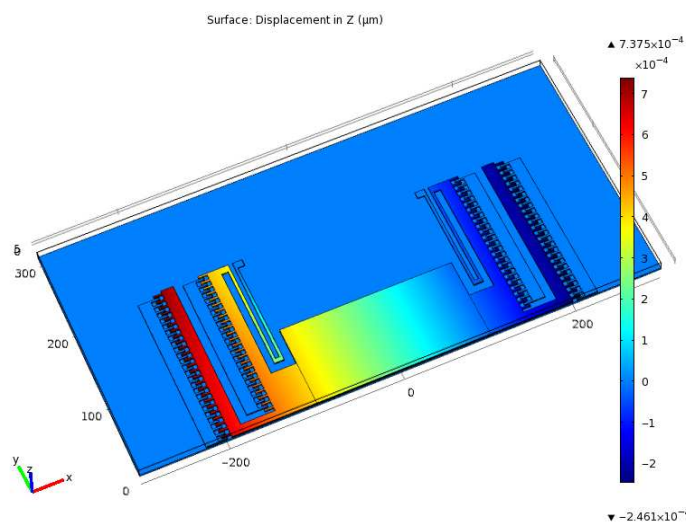


Figure 6: Displays displacement of the simulated MEMS along the z-plane for an applied electrostatic potential of .5V on Geometry 3.

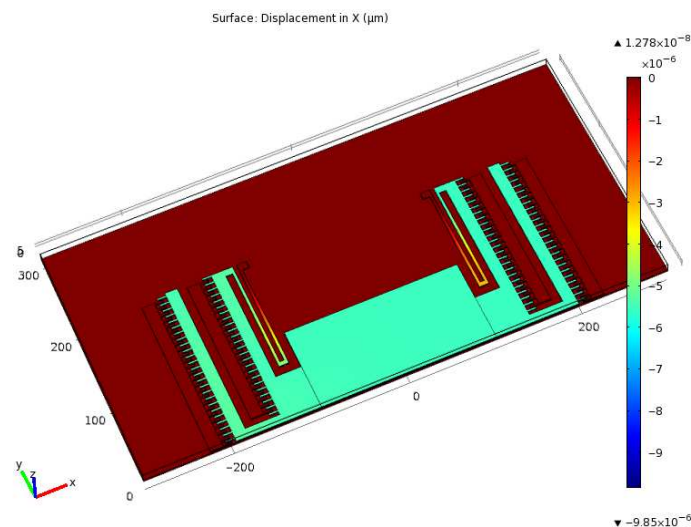


Figure 7: Displays displacement of the simulated MEMS along the x-plane for an applied electrostatic potential of .5V on Geometry 3.

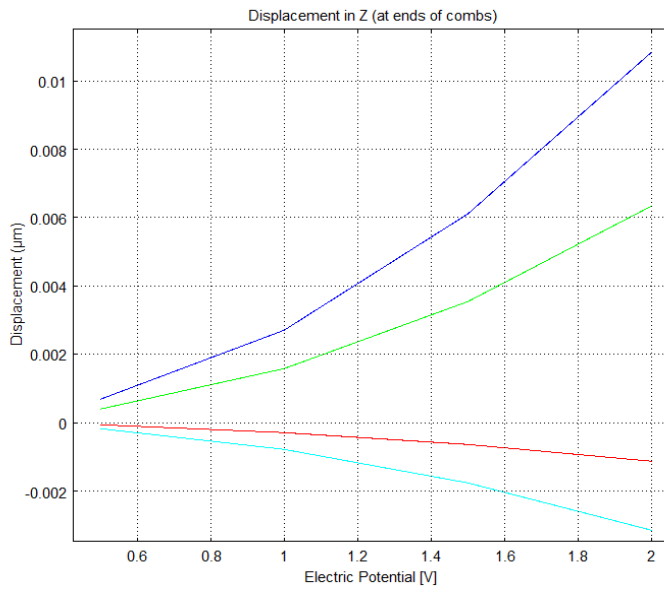


Figure 8: Lines indicate the progression of displacement, in the z-plane, of the four electrode ends in Geometry 3 for increasing electric potentials.

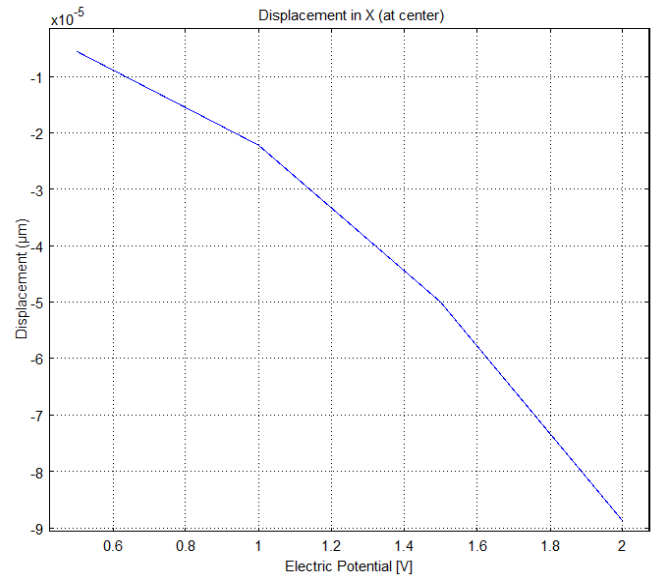


Figure 9: Illustrates the progression of x-plane displacement for Geometry 3's MEMS for increasing electric potentials.

The reasoning behind the MEMS devices bending so greatly is that the electric field lines around the MEMS are being distorted by the bottom plate. Because the bottom plate is so close to the moving plate (about 2 μm away), and due to the difference in permittivity between the poly-silicon bottom plate and the air between the plates, the field lines are distorted on the bottom of the moving plate. This distortion of the field lines on the bottom of the plate, but not on the top, causes asymmetric forces to be applied causing the device to bend.

The large unwanted out of plane movements present in our simulations could not be overlooked. In an attempt to find a solution to this problem, a new geometry was created. To stop the MEMS from displacing along the z-plane, two superstructures were added to Geometry 3. These structure would be 2 μm above the capacitors, the same distance as the bottom plate is to the moving plate. This new geometry creates symmetric boundary conditions on both the top and bottom of the plate, this causes the field lines around the MEMS to have equal field displacements thus damping any out of plane movement created by asymmetric field lines present in previous simulations. The missing half of the MEMS device was also simulated in

addition to the added superstructures (Geometry 4). The results of this model are displayed in Figures10-13.

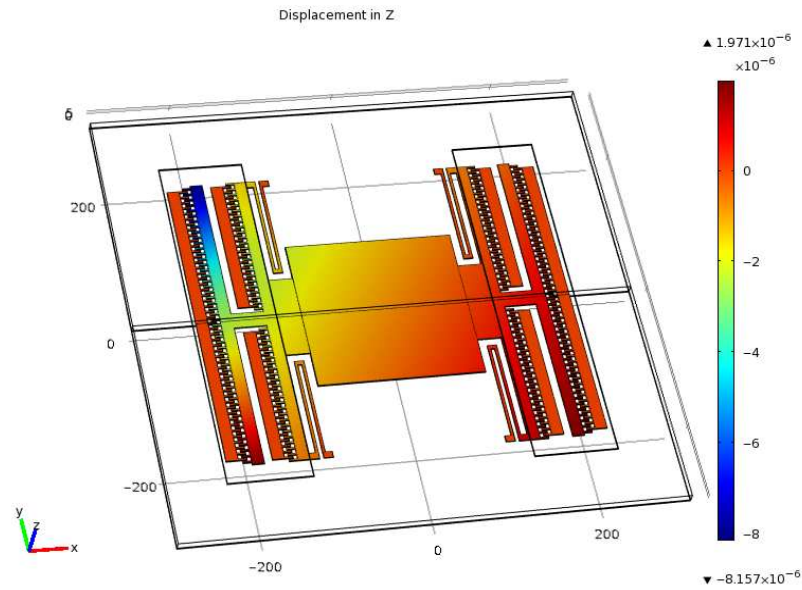


Figure 10: Displays displacement of the simulated MEMS along the z-planes for an applied electrostatic potential of .5V on Geometry 4.

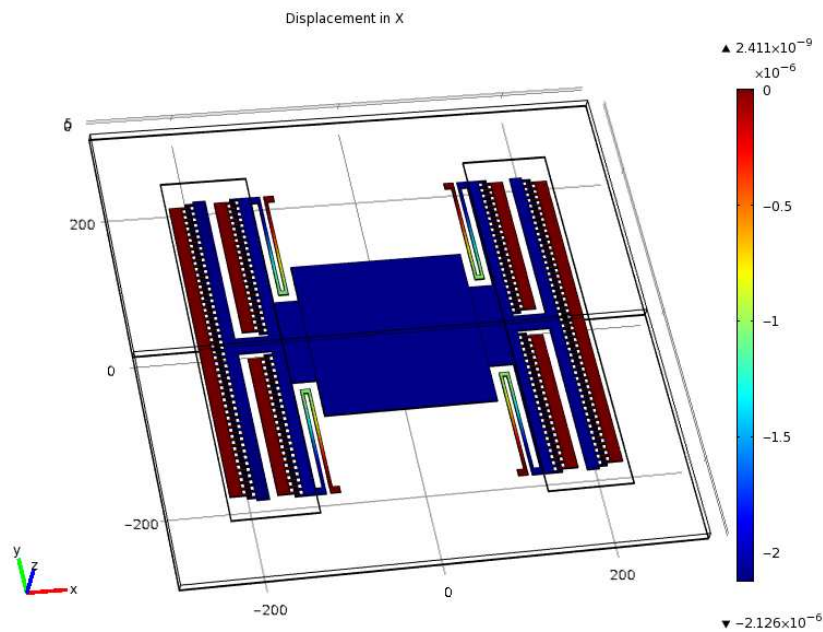


Figure 11: Displays displacement of the simulated MEMS along the x-planes for an applied electrostatic potential of .5V on Geometry 4.

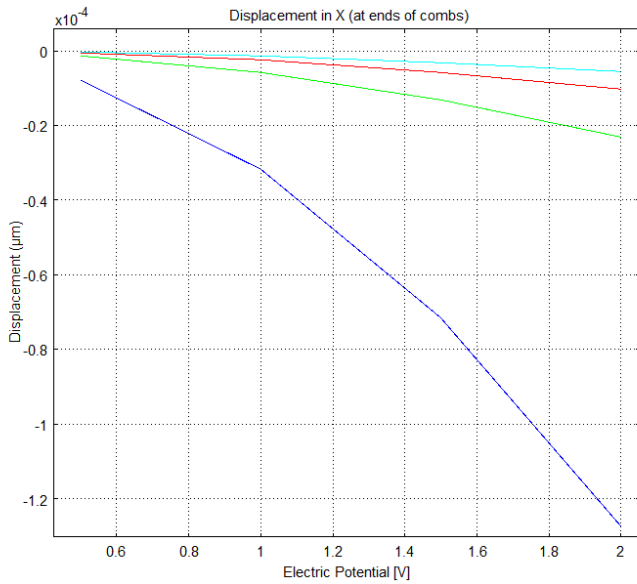


Figure 12: Lines indicate the progression of displacement, in the z-plane, of the four electrode ends in Geometry 4, for increasing electric potentials.

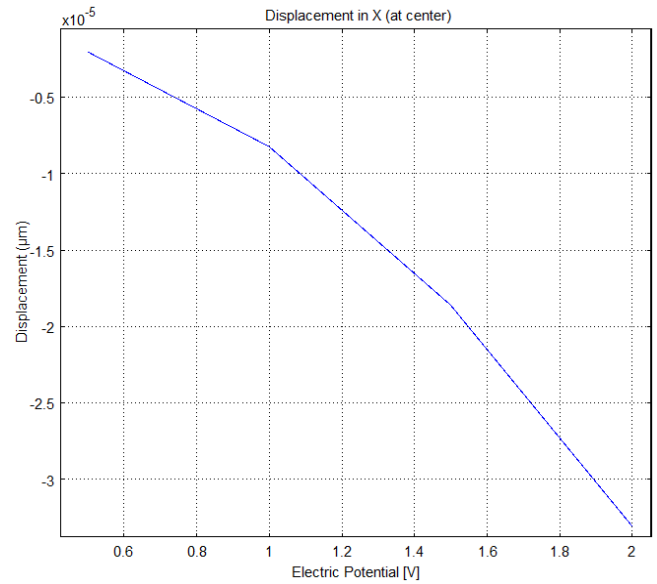


Figure 13: Illustrates progression of x-plane displacement for Geometry 4's MEMS, for increasing electric potentials.

Figures 10 and 11 illustrate the new model solved for the electric potential of 0.5 V, which has yielded very promising results. The addition of the superstrate greatly decreased the displacement of the moving plate along the z-axis. Though there is yet displacement in the z-plane this displacement plateaus as electric potential increases. This common trend is evident in all but the top-left-most electrode, the other electrodes exhibit this common trend which maintains a much smaller slope than that of the x-displacement (Figures 12 and 13). For Figure 12, the dark blue line corresponds to the displacement of the tip of the top left comb. The rest of the lines correspond, from top left to top right, to the colors green, red, and light blue.

IV. Conclusions

Our MEMS device was successfully simulated for the air phase. The simulations conducted for an air environment conclusively demonstrated an unfavorable displacement in the z-plane for the MEMS device. This unwanted out of plane displacement makes it difficult to extrapolate the x-planer distance between the capacitors, which is needed for our study of ^3He and ^4He . It is still possible that though there be a large out of plane displacement that, if this displacement is known exactly for a given set of parameters, that the x-displacement will be able to be extrapolated. Further modeling of the air simulation is still required. Modeling for an alternating voltage versus our currently modeled direct voltage is essential to study the mechanical resonant behavior of our model.

Though the results from our modeled MEMS device were concluded to be unfavorable, these results made it possible to design a successful alternate geometry of our MEMS device. The alternative geometry came in the form of added superstructures above the MEMS device's capacitors. Results from simulating this new geometry showed a large dampening in the z-plane's displacements when compared to our previous results. This allows us to more easily extrapolate the x-displacement from our capacitance measurements.

Modeling of the liquid helium simulation is yet required. It is important to understand how the density and viscosity of helium will affect the device, its displacements, and its subsequent capacitance measurements.

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References

- [1] M. Gonzalez, submitted to J. Low Temp. Phys. (2010).
- [2] M. Bao, Analysis and Design Principles of MEMS Devices, (Amsterdam, The Netherlands), p. 92-95, 150-159.
- [3] D. J. Griffiths, Introduction to Electrodynamics, 3rd ed. (Upper Saddle River, New Jersey, 1999), p. 104-105, 180
- [4] H. C. Svante Littmarck, F. Saeidi, program COMSOL, ed. 4.0a (COMSOL AB, Stockholm, Sweden)