Simulation of MEMS Comb-Drive Actuators for Use in Superfluid ^{3}He

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Analysis of capacitor-driven micro-electro-mechanical systems (MEMS) are conducted to characterize the devices for use in liquid ^{3}He experimentation. Analysis was performed through computer simulation using the multiphysics software package COMSOL. Through simulation, the relevant electrostatic and mechanical properties of our device, as well as its various vibrational modes, were identified. Phenomena affecting our device, such as electrostatic levitation, were carefully reviewed and studied. Simulations are in accord with optical measurements taken from the actual devices. Using the data collected from these simulations, future generations of the MEMS will be designed and improved for use in liquid ^{3}He experimentation.

INTRODUCTION

Micro-electro-mechanical systems (MEMS) are a technology defined by its minuscule size. Comprised of systems of electrical and mechanical components, MEMS form sensors and actuators of the micron to sub-micron level. Through the use of these systems, most every kind of sensing is possible, including: acceleration, magnetic fields, temperature, pressure, and many others. In many cases these micro-systems outperform their macro counterparts.[1]

Like integrated circuits, MEMS technologies are formed by batch processes allowing for the cheap production of these devices. Because MEMS allow for high performance sensing at low costs, MEMS devices are widely used in a number of commercial ventures and can be found all around you today. MEMS are commonly used as crash air-bag deployment systems in cars and as gyroscopes for smart-phones and gaming systems.[2]

MEMS technologies are not limited to commercial use; because of their superior sensitivity to macro sensors, many scientists are exploring the benefits of incorporating MEMS devices into their experiments. A perfect mixture of mechanical and electrical components, along with their small size and potential for ultra-high resolution measurements, make MEMS an ideal tool to be used in experimental research and can allow scientists to study and analyze systems previously thought unexplorable.

Seeing the incredible prospects that MEMS hold for science, our lab group, headed by Prof. Yoonseok Lee, is pioneering a new detection technique using MEMS to probe the inner workings of quantum fluids.

MEMS Design

The ultimate goal of our efforts is to create MEMS devices capable of studying the properties of quasi-two-dimensional superfluid ^{3}He operating at sub-milli-kelvin temperatures. To this end, we have designed and fabricated two types of MEMS comb-drive devices (Figure 1); the fabrication was conducted by the company MEMSCAP using the batch fabrication process PolyMUMPS.

The devices are similar in geometry, being made of two main layers, as illustrated in Figure 2. The bottom layer is made of a slab of nitride with a thin layer of heavily-doped polysilicon sitting atop it, while the top layer is made entirely of heavily doped polysilicon. The top layer is elevated above the bottom layer by four serpentine springs and is comprised of a large 200 x 200 μm^2 center plate with comb-electrodes attached on either side, seen in Figure 3. The electrodes attached to the suspended top plate form capacitors with opposing electrodes fixed to the substrate. The electrodes on our devices are comb-toothed in order to increase the effective surface area of the capacitors. This results in an increase in the signal to noise ratio in our device, allowing for larger capacitances for the same input voltage.

The gap formed between the top and bottom layers of our two MEMS devices is where the quasi-two-dimensional superfluid film will be formed. The electrode pairs are to detect lateral displacements in our device as well as create capacitor-driven lateral actuation. When a direct current or voltage is applied to one side of the fixed comb-electrodes, displacement results in our device, but if this lateral actuation is driven by an alternating current the device will oscillate. By comparing the device's oscillation frequency before and after the device is submerged in superfluid, the detection of frictional effects caused by the superfluid film formed between the device and substrate can be isolated and analyzed.

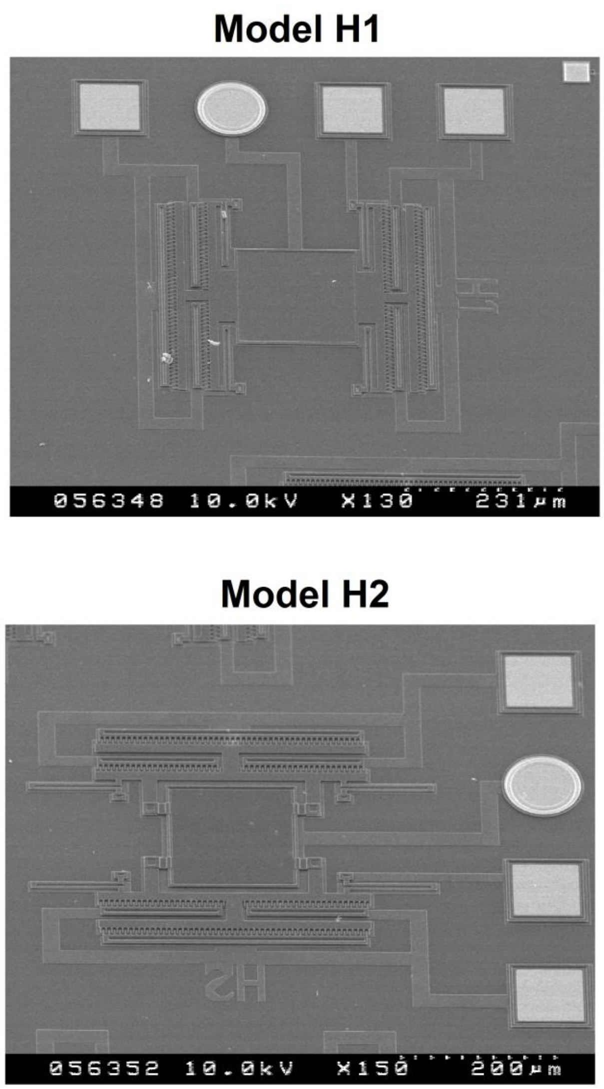

Figure 1. Images taken using a scanning electron microscope of two MEMS devices used as a novel detection technique for the study of superfluid ^{3}He phase transitions. Fabricated using a PolyMUMPS process, these devices form quasi-two-dimensional films between the oscillating top layer and the substrate.

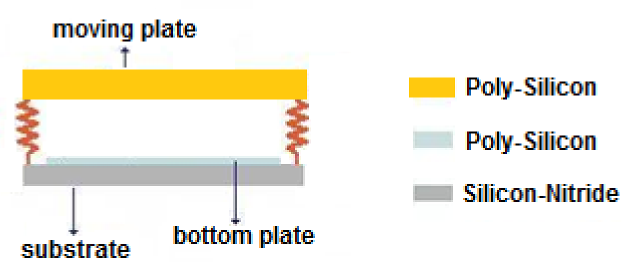

Figure 2. The two MEMS devices H1 and H2 are separated into two layers. The bottom later is made of a 0.6 μm silicon-nitride slab with a 0.5 μm heavily-doped, polysilicon layer atop it, and the top player, being 2.0 μm thick, is made entirely of heavily-doped poly-silicon.

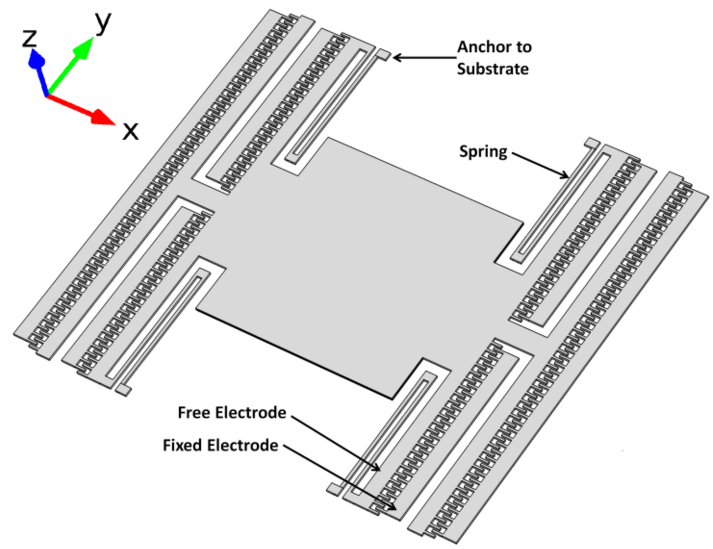

Figure 3. Illustration is of a CAD design of our MEMS device depicting the top layer of our H1 model. Labeled structures are similar in both our H1 and H2 devices.

Our two models, named model H1 and H2, have only a few differences in their geometry. The main and most important difference is the gap size formed between the substrate and top plate of our models, for this is where our quasi-two-dimensional film will be formed. For H1, this gap size is approximately 0.75 μm, and for H2, the gap size is approximately 1.25 μm. It is important to note that, in both models, the electrodes attached to these center plates are situated at the same height even though the center plates are not, and so the capacitive actuation in both devices should respond similarly.

Not only do the gap sizes differ between models H1 and H2, but the layer comprising their center bodies also differ. Model H1's body is formed out of the Poly1 layer in the PolyMUMPS fabrication process, while model H2's body is formed from the Poly2 layer.

The last difference between the H1 and H2 models is the spring orientation, as can be seen in Figure 4. The geometry of the spring itself is identical in both models; the difference is in the placement of these springs. Model H1 has its springs oriented inwards (towards the body) and attached at the very edges of the comb-electrodes. Model H2 has its springs oriented outwards (away from the body) and attached lower on the comb-electrodes than are the model H1 springs.

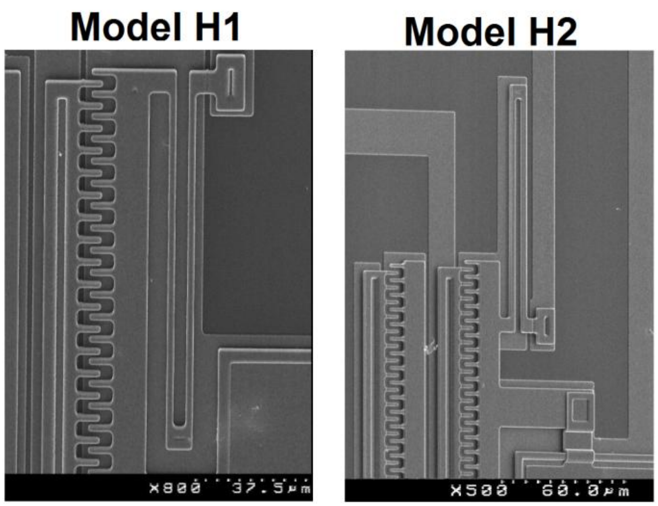

Figure 4. SEM images of the springs of both H1 and H2 models. The spring geometries of both models are identical but are attached at different points on the comb-electrode and are oriented differently with respect to the central plate.

Actuation

One of the most important aspects of our device is how it actuates. Both of the models fabricated actuate via capacitive forces. This section will be a brief review of capacitive forces as they pertain to our system, and calculations of the electrostatic forces found in our systems.

The capacitors on both our MEMS devices are comb-toothed, as seen in Figure 5. This means that the capacitive forces that drive our systems are not caused by the interplay of the combs themselves, but by the interplay of the interlocking comb teeth. The interlocking teeth in our device act as capacitors between themselves.

There are two main ways to displace a capacitor: by means of a normal force or a tangential force. Due to the interlocking of the teeth of the device, the sum of all the normal forces between the teeth will cancel out. For our devices, it is a tangential force between the capacitor plates that drives actuation.

Varying capacitance with tangential displacement corresponds to varying the area parameter in our capacitive equation: $C = \varepsilon_r \varepsilon_0 \frac{A}{d}$. The area of our overlapping capacitor plates can be thought of as a height (h) times a variable length ($x_0 + x$). This gives us a capacitance of the form $C = \varepsilon_r \varepsilon_0 \frac{h(x_0+x)}{d}$ (Figure 5). To extrapolate a force from this, we take the derivative of this value, which results in: $\frac{dC}{dx} = \varepsilon_r \varepsilon_0 \frac{h}{d}$.

Plugging this into our force equation we get: $F = -\frac{dW_t}{dx} = \frac{1}{2} V^2 \frac{dC}{dx} = \varepsilon_r \varepsilon_0 \frac{h}{2d} V^2$, though this is just the tangential force caused by one capacitor pair formed by two neighboring comb teeth. In order to get the full applied force of our comb-capacitor system we need to multiply this force by the number of capacitors in our comb- system; $F = N \varepsilon_r \varepsilon_0 \frac{h}{2d} V^2$.

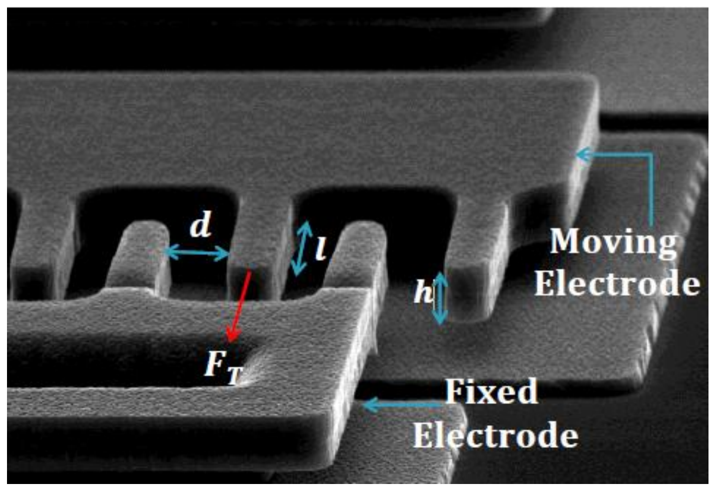

Figure 5. SEM image of the comb-teeth structures in our MEMS devices, with labeled parameters relating to the force calculation for our system. Models H1 and H2 both have identical comb-teeth structures.

This, however, is not the whole story. Due to the conducting nature of the entire comb-electrode system, the field lines of our capacitors (formed between the teeth of our electrodes) will be attracted to the body of the device, resulting in fringe fields: $C = \varepsilon_r \varepsilon_0 \frac{h(l+x)}{d} + C_f$. Luckily, this term can be neglected, because the fringe capacitance does not change with displacement, leaving our value, $\frac{dC}{dx}$, the same so long as the fingers of the comb-electrode are sufficiently long (Figure 6).[3]

Knowing the capacitive forces affecting our device, we can extrapolate this to find the form of the displacement of our device. There are two counteracting forces in our device that affect the displacement of our system, the capacitive force derived, and the spring force kx, where k is the spring constant of our device (Figure 7). Subtracting these two forces from one another and setting the solution to be zero, $(N\varepsilon_r\varepsilon_0\frac{h}{2d}V^2 - kx = 0)$, we arrive at the form for the maximum displacement of our MEMS systems: $x = N\varepsilon_r\varepsilon_0\frac{h}{2kd}V^2$.

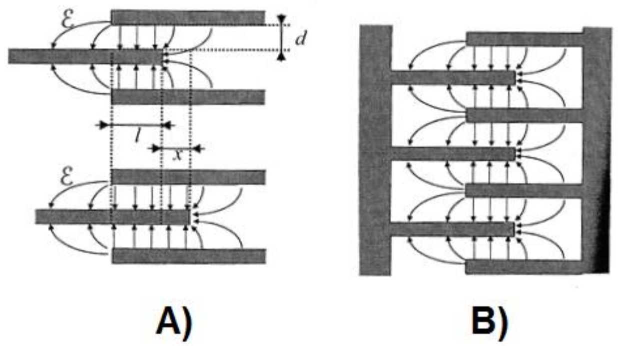

Figure 6. Figure A) illustrates the fact that, so long as the comb-teeth are sufficiently long enough, the fringe fields are independent of displacement. Figure B) shows that if the comb teeth are not sufficiently long enough the body of the comb-electrodes contributes to the fringe fields.[3]

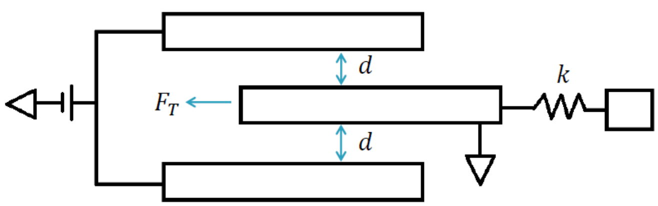

Figure 7. Illustration modeling the interplay of the biased fixed electrodes causing capacitive tangential forces to be applied to our system, and the forces of the springs in our system resisting the capacitive forces.

Simulation

Understanding how our device actuates, we can move onto simulation. To simulate our two MEMS designs, we used commercially available multiphysics simulation package COMSOL. COMSOL is a program capable of both creating and modeling physical scenarios. COMSOL has the ability to create or import computer aided designs (CADs), in which you can specify the partial differential equations you want to solve for, along with any boundary conditions applicable to your model. Using this model, COMSOL solves the partial differential equations applied by the mathematical method of finite element analysis. Finite element analysis is the numerical technique of approximating solutions to partial differential equations by taking a model, separating it into a number of discrete smaller geometric entities, solving the partial differential equations applied to the model for these smaller entities, and then integrating the solutions.

COMSOL is a very memory intensive program. Initially, simulations were conducted on a quad-core desktop PC having 4GB of memory. Using this setup, harmonic simulations of our MEMS devices had an average run time of one week. With the recent release of COMSOL 4.0, cluster computing capabilities were given to all license holders. Since then, COMSOL simulations have been moved over to the Hydra clusters at the University of Florida where run times have been cut down significantly, to an average of one hour.

Harmonics. To characterize our MEMS designs we needed to know the harmonics of our system, the frequencies we should expect our systems to resonate at, and the modes these resonances corresponded to. COMSOL calculates the harmonics of a model by first assuming that a harmonic displacement field is affecting the model then continuing to compute a frequency response study for the model. Figure 8 and Figure 9 show the four harmonic modes of our H1 and H2 devices simulated using COMSOL. The PolyMUMPS fabrication process for these devices has a resolution of 0.25 μm and so the four modes in the illustration are labeled as having a maximum and minimum resonant frequency corresponding to an ideal spring arm width (3.0 μm) and a spring arm width 0.5 μm thinner than the ideal (2.5 μm). Apart from these modes, there are also higher order modes for both models. These harmonics correspond to unrealistic motion of our device, and are simulated to occur at much higher frequencies.

Each of our two models have the same four harmonic modes, albeit they occur at different frequencies and in a different order: one in plane (x-displacement), one out of pane (z-displacement), and two axis pivot modes (x-pivot and y-pivot). This is as expected; the spring geometries of our two systems are identical and so the spring constants of our two devices are identical.

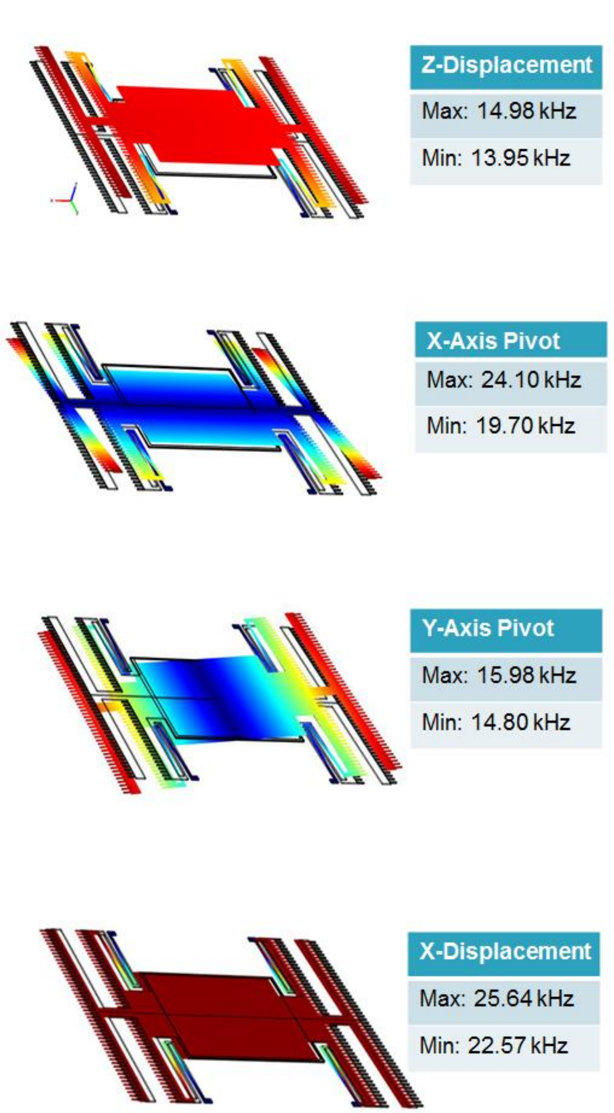

Figure 8. Simulated harmonic modes of the H1 MEMS design. Modes are in order of increasing frequency from top left to lower right.

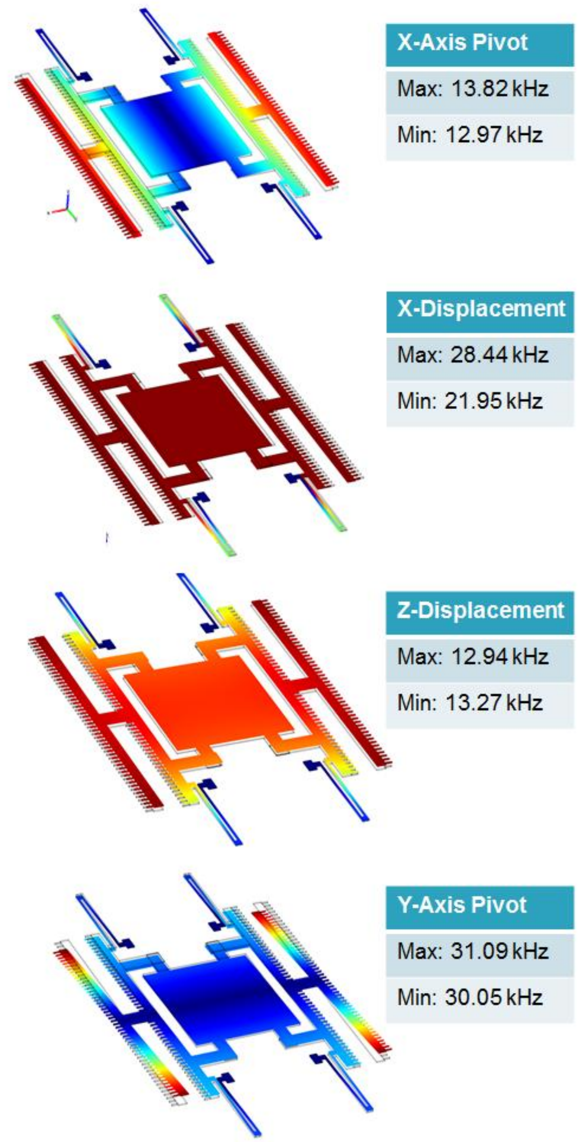

Figure 9. Harmonic modes simulated for our H2 MEMS design. Modes are the same as the H1 model, but occur at different frequencies

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Correlation

The purpose of the analysis and simulation of the MEMS devices was to establish a baseline against which normal operational of our MEMS could be measured. During initial experimental study of these two MEMS designs, they were put into a vacuum and a frequency sweep was conducted.

Two resonance peaks were found for our H1 system at 14.560 kHz and 23.101 kHz, but only one peak for our H2 system, at 26.692 kHz. These values match up well with the simulated values for the harmonic modes. The two experimentally excited modes for H1 correspond to the simulated x-displacement mode (22.57 kHz) and the y-axis pivot mode (14.80 kHz). The sole excited mode for H2, at 26.692 kHz, is higher than the nearest ideal harmonic mode, that being the x-displacement mode at 21.95 kHz. Taking into account the lithography error and the maximum frequency for this mode, 28.44 kHz, the simulated harmonics match well with the experiment results. This may also mean that our experimental H2 MEMS chip has significant lithography error.[4]

Only one mode was expected to be excited experimentally per device. The expected mode, x-displacement, is the mode our system is designed to excite. The y-axis pivot mode, excited in our H1 model, was later found to be excited by a force commonly called the levitation effect.

Levitation Effect

The electrostatics in our systems caused an additional unintended effect, common among comb actuators, called levitation effect. Levitation is an effect caused by the imbalance of the electric field lines surrounding the teeth of comb actuators, resulting in a net vertical force to the grounded electrode teeth. This phenomenon comes about as a consequence of the necessity to shield MEMS devices from relatively large vertical fields, which would interfere with proper electrostatic actuation. This shielding takes the form of a heavily doped polysilicon ground plate beneath the device, and it is this plate that causes the imbalance of field lines (Figure 10).

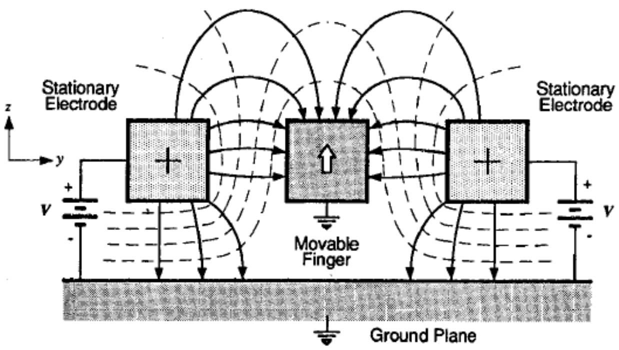

Figure 10. Due to the imbalance of the electric field lines between our interlocking comb-electrode teeth, there is a net vertical displacement acting upon our system. In this image, the positive blocks represent the fixed comb electrode teeth of our system, and the grounded central block represents a sandwiched fixed electrode tooth in our system.[5]

To create lateral displacement in our device, the central plate of our systems have to be grounded in order to optimize the attractive forces induced by the capacitors. Furthermore, to keep our central plate from being attracted to the substrate, they need to be at the same potential, and so the substrate must also grounded.

The levitation effect occurs when the biased fixed electrode teeth in our system induce an opposing charge on both the grounded electrode teeth, and the grounded ground plate. The induced image charges repel one another and cause the device to have a net vertical force. This is most easily understood by evaluating the forces acting on the system using energy methods: $E = QV$ where E is the stored electrostatic energy, Q is the charge induced on the grounded (moving) comb fingers, and V is the electric potential. Differentiating this with respect to the normal (z-direction) we find that the lateral forces in our device take the form: $F_z = \frac{\partial E}{\partial z} = Q\frac{\partial V}{\partial z} + V\frac{\partial Q}{\partial z}$. Looking to this equation for guidance, it is easy to tell from Figure 10 that the charge is not equal to zero ($Q \neq 0$) in our system, nor is the change of electric potential as a function of vertical displacement ($\frac{\partial V}{\partial z} \neq 0$), which then makes it very clear that the vertical levitation force in our system can in no way be zero ($F_z \neq 0$).[5]

CONCLUSIONS

Experimental results of our two MEMS designs match the simulations of these devices to high precision. Harmonics produced experimentally were found to relate to known actuating forces in our devices and are consistent with theory. Further simulation will need to be conducted on the electrostatics of our H2 model to study why there was no experimentally excited levitation effect actuation resulting in an y-axis mode pivot harmonic. Further work will also be conducted on dampened and displaced harmonics correlating to our device in air or liquid boundaries, and with DC biased displacements affecting the harmonics.

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