IMPROVED COMB DRIVE SUGAR CODE

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Comb drives have become part of a standard set of MEMS actuators. With the explosive growth of MEMS devices, a number of simulation programs have been created in order to help designers. Herein one specific program, SUGAR, is examined. Several assumptions and approximations are embedded within the code of this program. This study seeks more exacting theoretical equations by both fitting simulation data to experimental data and comparing simulations to experiments. Two improvements, most especially the introduction of a parameter, A, which is dependent upon thickness and finger gap, are suggested.

I. INTRODUCTION

Laterally driven comb drives are the most common components of micro electro-mechanical systems (MEMS) devices in use today. The field of MEMS has experienced explosive growth in the past decade. As the field matures, more sophisticated methods of simulating expected results from novel MEMS devices are necessary (**1, 2**). SUGAR, a simulation tool to help address this need, uses nodal methods to analyze MEMS structures (**3**). Ever since the creation of lateral comb drives 1989, approximations have been used to calculate the critical parameters such as resonant frequency and Q, the quality factor (**4**). SUGAR makes use of these approximations, as well. There are cases, however, where they do not hold well (**5**). This study attempts to install the more fundamental equations back into SUGAR calculations and examines cases in which there are significant discrepancies between the approximations and the more general equations. There are several approximations typically made. Many of them will be discussed herein, however only electrostatics, specifically capacitance, will be studied in detail

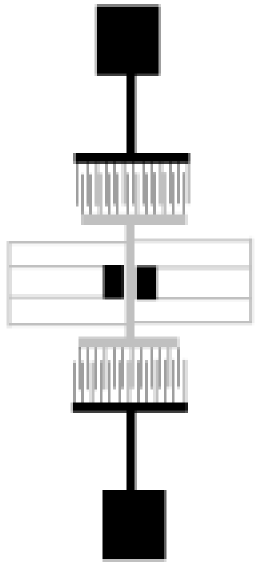


fig 1: Comb drive. Dark areas are immobile

II. THEORETICAL BACKGROUND AND DESIGN

A resonating lateral comb drive such as that in figure 1 experiences forces due to electrostatics, mechanics, and friction. The mechanical force is beam bending, given as follows:

$$\frac{\frac{\partial^2 y}{\partial x^2}}{\left[1+\left(\frac{\partial y}{\partial x}\right)^2\right]^{3/2}} = \frac{M}{EI} \qquad (1)$$

where y is the direction perpendicular to the beam and it experiences a moment, M. Dimension x is along the length of the beam, E is Young's modulus, and I is the moment of inertia of the beam (**6**). Equation 1 can be simplified to

$$\frac{\partial^2 y}{\partial x^2} = \frac{M}{EI} \qquad (2)$$

when $\partial^2 y / \partial x^2$ is much smaller than unity. SUGAR uses equation 2. It may therefore lose some accuracy, especially if materials with Young's moduli smaller than polysilicon are used.

At high frequencies, the frictional force due to air is significant. Typically Couette flow of air underneath the structure is assumed. However neither Couette nor Stokes flow accurately predict damping. Q factors based upon such models are consistently higher (better) than experimental data (**7**).

Electrostatic forces are also typically approximated. Equation 3 is the general expression to describe such forces in comb drives:

$$F_e = -\frac{\partial U_{total}}{\partial x} = \frac{1}{2} V^2 \frac{\partial C}{\partial x} \qquad (3)$$

where F_e is electrostatic force, U_{total} is total energy, V is voltage, and C is capacitance Typically, the parallel plate approximation is made for capacitance, such that

$$\frac{\partial C}{\partial x} = \varepsilon_0 \frac{t}{g} \qquad (4)$$

where ε_0 is the permittivity of free space, t is material thickness, and g is gap between neighboring comb fingers. However, since a thin native oxide is always present, ε_0 is not a good approximation for the true permittivity since roughly ½ of the voltage drop across the gap is experienced in the through the oxides (**8**). Also, experimental evidence (**4**) has shown that the parallel plate approximation can be significantly erroneous, especially as t/g shrinks down to unity and fringing electric fields become a concern. While that ratio can be maintained high for many processes, forcing it so may hurt attempts to integrate a lateral comb drive with other structures.

To improve the accuracy of SUGAR's simulations, all three of these issues need to be addressed in the code. However, this study focuses only upon the approximations to electrostatic force. Simulations using the old code are compared to new code and experimental data.

III. EXPERIMENTAL RESULTS

References **4, 7, 9-12** contain experimental data that have been compared to previous code and revised code of SUGAR. Figure 2 is the comb drive structure that was used in SUGAR to obtain the data. Fitting simulations to experimental data, the following corrections were made: (1) Applied voltage was multiplied by 0.495. This agrees with the conclusion from ref **8**. The ratio of voltage drop within the air versus total voltage drop is not always 0.495, but it was accurate enough over the range examined. (2) A fitting parameter, A, was added to equation 3.

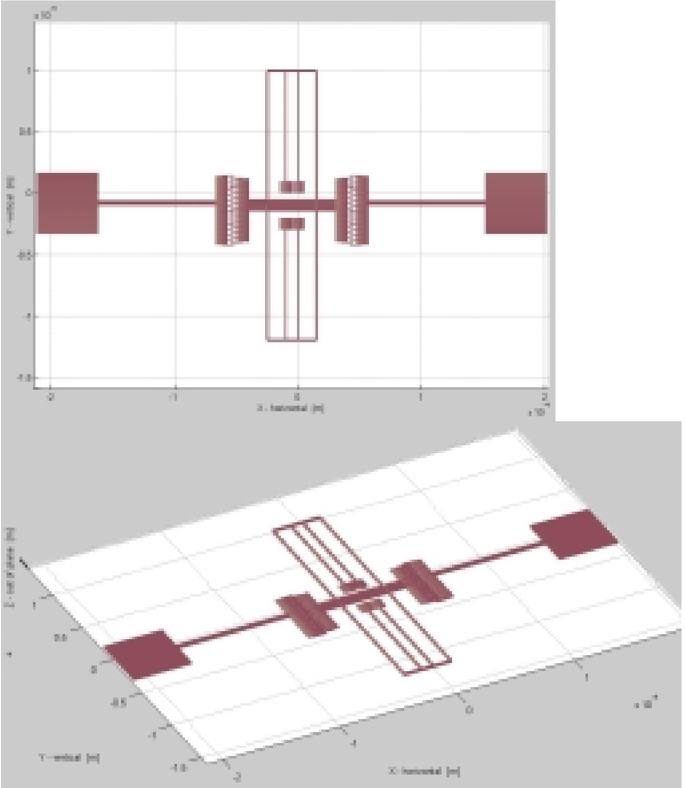


Fig 2: Comb drive structure used in SUGAR

$$A = \left(1 + 15.2 \times e^{-\left(\frac{t}{g}\right)^{3/2}}\right) \qquad (5)$$

Figure 3 is a comparison of the two simulations to experimental data from **4**. The model is still predicting a somewhat smaller effect of beam length upon transfer function than actual data demonstrates, however it is significantly improved from the original simulation model. Figure 4 shows an update to the SUGAR code. This includes parameter A, but not voltage changes.

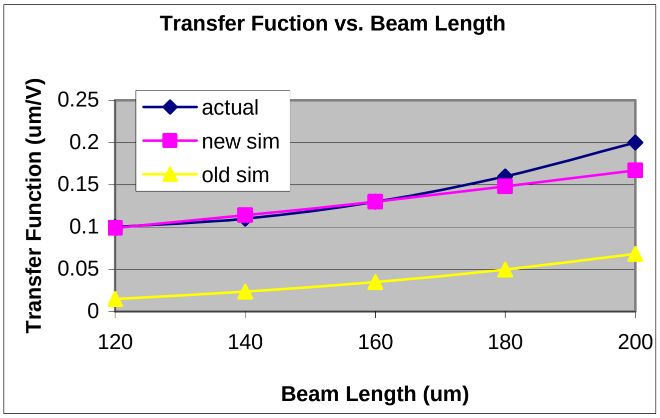
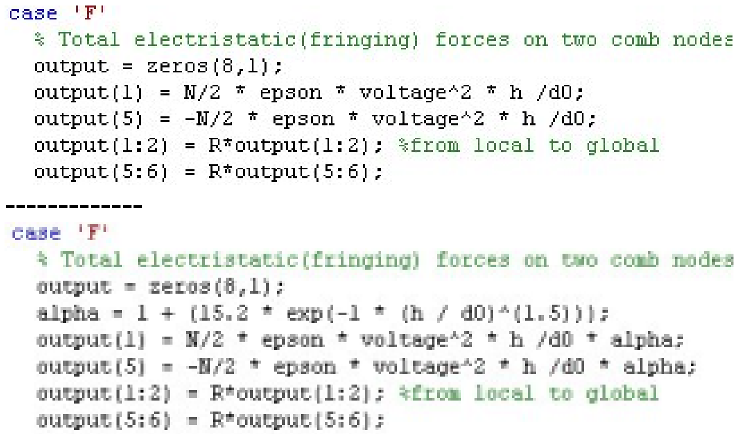


Fig 3: Comparison of experimental data with SUGAR new and old code.

Another parameter that plays a strong role in fringing field effects is the gap between a comb finger and an opposing comb backbone. That is, as the actuator is displaced further, this



```
case 'F'
  % Total electristatic(fringing) forces on two comb nodes
  output = zeros(8,1);
  output(1) = N/2 * epson * voltage^2 * h /d0;
  output(5) = -N/2 * epson * voltage^2 * h /d0;
  output(1:2) = R*output(1:2); %from local to global
  output(5:6) = R*output(5:6);
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case 'F'
  % Total electristatic(fringing) forces on two comb nodes
  output = zeros(8,1);
  alpha = 1 + (15.2 * exp(-1 * (h / d0)^(1.5)));
  output(1) = N/2 * epson * voltage^2 * h /d0 * alpha;
  output(5) = -N/2 * epson * voltage^2 * h /d0 * alpha;
  output(1:2) = R*output(1:2); %from local to global
  output(5:6) = R*output(5:6);
```

Fig 4: SUGAR code. Top is old code, bottom is new finger-backbone gap closes. Normally the field between these two areas is ignored, considered insignificant. Unfortunately, this parameter could not be evaluated. There is no manner in which to describe an increasing electrostatic field as the motion of the actuator changes.

IV. CONCLUSIONS

This study brought to attention several theoretical approximations that are typically used in MEMS device characterization that might be worthy of addressing. Electrostatic forces were then specifically examined, especially in cases where the thickness/gap ratio was small. Using experimental data from the references, an improved model was created to account for the fringing fields.

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