Finite Element Analysis of the Vertical Levitation Force in an Electrostatic MEMS Comb Drive Actuator

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Abstract. A vertical levitation electrostatic comb drive actuator was manufactured for the purpose of measuring piezoelectric coefficients in small-scale materials and devices. Previous modelling work on comb drive levitation has focussed on control of the levitation in standard poly-silicon devices in order to minimize effects on lateral modes of operation required for the accelerometer and gyroscope applications. The actuator developed in this study was manufactured using a 20 µm electroplated Ni process with a 25 µm trench created beneath the released structure through chemical wet etching. A finite element analysis using ZINC was used to model electrostatic potential around a cross section of one static and one movable electrode, from which the net levitation force per unit electrode was calculated. The model was first verified using the electrode geometry from previously studied systems, and then used to study the variation of force as a function of decreasing substrate-electrode distance. With the top electrode surfaces collinear the calculated force density is $0.00651 \varepsilon_0 V^2 M \mu m^{-1}$, equivalent to a total force for the device of 36.4 µN at an applied voltage of $V_M=100$ V, just 16% larger than the observed value. The measured increase in force with distance was smaller than predicted with the FEA, due to the geometry of the device in which the electrodes at the anchored ends of the supporting spring structure displace by a smaller amount than those at the centre.

1. Introduction
PiezoMEMS devices incorporate the use of piezoelectric films [1, 2] into Micro-Electro-Mechanical Systems for novel, miniaturised components such as resonators [3] and filters for wireless applications [4], switches in RF applications [5], inertial sensors [6] and energy harvesting devices [7]. Successful commercialisation of such applications requires accurate metrology for evaluating the properties of the piezoelectric films. Whilst there are several optical methods of quantifying the strain response of micro-scale piezoelectric materials to an applied voltage, the measured displacement is convoluted with the substrate clamping effects of the underlying silicon layers or substrate. The measurement piezoelectric response will therefore contain derived quantities from the mechanical properties of the silicon, which are not always easily determined. As such, a direct measurement of the piezoelectric material is preferable.

To this end, a MEMS piezoelectric measurement system was designed, built and tested for the evaluation of piezoelectric coefficients in small-scale systems. The system consists of an electrostatic comb drive actuator, which imparts a known force to the sample under test, and
isolated electrical routing to an off-chip, ultra-low charge measurement circuit, to calculate the piezoelectrically induced charge. Full details of the MEMS design and operation can be found in reference [8]. A simulation of the free displacement of the vertical levitation actuator is shown in figure 1. A central plate is under-etched and suspended above the substrate by means of eight serpentine beams. ‘Finger’ electrodes of width 10 $\mu$m and lengths between 150-400 $\mu$m were attached to the supporting beams, and interdigitated with equivalent electrodes pointing towards the centre of the device, attached to the substrate.

Vertical levitation occurs within a comb drive actuator because of an asymmetry in the geometry and electrical bias within the structure. Figure 2 shows a cross section of a set of comb fingers: the stationary electrodes are biased to a voltage of $V_M$, and the movable electrode is electrically grounded along with the silicon substrate. A vertical force on the rotors is established in the direction away from the substrate, due to the interaction between surface charges on the electrodes and the surrounding potential, which aim to pull the comb finger upwards to a height at which the voltage seen by the top and bottom surfaces is equal. In reality this equilibrium position is dictated by the interplay between the electrostatic force, the restorative spring force from the flexural supporting beams of the device which anchor the comb fingers to the substrate, and the force due to gravity on the suspended structure.

In the piezoelectric measurement, the sample is clamped directly above the MEMS device,
and the fully blocked force is transferred to the piezoelectric. Care must be taken not to significantly depress the central pad of the MEMS device with the contact to the sample, as it will have an effect on the size of the applied force. Since all previous investigations of comb drive levitation [9, 10, 11, 12, 13, 14, 15, 16] have looked at the variation in force with positive displacement from the neutral position (because the force is always away from the substrate, regardless of the polarity of $V_M$), it was necessary to simulate the effect of movements towards the substrate for the full characterisation of the device described above.

2. Experimental Details
A finite element package developed in house at NPL [17] was used to compute the levitation force on the movable electrodes. The problem to be solved in this case is to determine the electrical potential field through the cross section of the comb fingers, and from this to derive the electric and displacement fields. Following the methodology of Chyuan et al. [13], we evaluate the electric field normal to the movable comb finger surfaces ($E_n$, $n = 1, 2$) and calculate the net levitation force per unit length of electrode as:

$$F_n = \int_B -\frac{\varepsilon_0 E^2_n}{2} dB$$

where $B$ is the line across the horizontal edge of the conductor. The total force is simply the difference in the path integrals between the top and bottom surfaces.

3. Results
To check the validity of the model, the code was first run with the geometry evaluated by Chyuan et al. [13], and experimentally tested by Tang et al. [18], where electrodes of width 4 $\mu$m and thickness 2 $\mu$m are laterally separated by a distance of 2 $\mu$m, with a gap to the substrate of also 2 $\mu$m. For the finite element model, a 2D mesh was created 40 $\mu$m in height and 6 $\mu$m in width. Nodes were created every 0.1 $\mu$m in the lower half of the mesh, with the $z$ step increasing to 0.5 $\mu$m in the top half, far away from the electrodes where the electric field is expected to be small. In the simulation the following Dirichlet boundary conditions were applied. All nodes within the stationary electrodes were set to 1 V. The nodes within the movable electrodes, and on the top and bottom edges of the mesh (the air furthest away from the comb fingers, and the grounded substrate respectively) were set to 0 V. The voltage at all other nodes was allowed to vary over $2 \times 10^5$ iterations, obeying the relation:

$$-\nabla \cdot (\varepsilon \varepsilon_0 \nabla V) = 0$$

Examination of the initial and final energies of the system indicated that a solution had been found to good accuracy.

The electric field across the top of the bottom surfaces of the movable electrode was calculated by the gradient of the electric potential in the $z$ direction, and is shown in panel A of figure 3. The results closely match those presented by Chyuan et al. [13] who evaluated the electric field using a boundary element method (BEM). These data were used to evaluate the net vertical force per unit length of electrode as described in equation 1, found to be $0.1143 \varepsilon_0 V^2_M/\mu m$. The simulation was then repeated with the central electrode translated upwards in $z$. As can be seen in panel B of figure 3 the levitation force passes through zero at a point where the electric field intensity around the top and bottom of the device is equal. Moving the electrode above this reverses the sign of the force, pulling the suspended plate back towards the substrate. The equilibrium point was calculated to be 1.12 $\mu$m, in comparison with a value of 1.19 $\mu$m predicted by Chyuan et al. and the experimentally verified position of 1.22 $\mu$m by Tang et al.
Figure 3: (Colour online) Panel A: The magnitude of the electric field along z along the top and bottom surfaces of the conductor (solid lines). The data reproduced from Chyuan et al is plotted using squares and circles for the same quantities. Panel B: Net vertical force density acting on the movable electrode when the comb finger has been displaced vertically by z.

The FEA input files were then adapted to describe the size of the devices manufactured in this study, with 10 µm wide electrode fingers, 20 µm in thickness are separated laterally by a 15 µm gap and placed 25 µm above the Si substrate surface. Since most of the dimensions are scaled by a similar factor between the two geometries, the results of the FE analysis are also qualitatively similar. The simulation was carried out with the central electrode translated downwards in $\Delta(z)$ in steps of 2 µm. The simulation results at $\Delta(z) = 0$ µm and -20 µm are shown in figure 4, and the calculated force density profile as a function of z is shown in figure 5.

In depressing the comb finger towards the substrate, the force density first rises at a rate of $0.0024 \varepsilon_0 V^2_M / \mu m^2$, and the system becomes non-linear below $\Delta z \sim -4$ µm. At $\Delta(z)=0$, the calculated force density is $0.00651 \varepsilon_0 V^2_M / \mu m$, only 6% of the value found in the 4×2 µm$^2$ poly-Si comb fingers. The difference arises from the relative 20% increase in the electrode-substrate gap which decreases the electric field asymmetry between the top and bottom surfaces. The intra-electrode distance is also very much increased to allow for the design rules of electroplated Ni process. The calculated force density per unit length was multiplied by the total length and number of comb fingers, equal to 63.1 mm. Multiplying this by a factor of $\varepsilon_0 \times V^2_M$ gives a total net vertical force of 36.4 µN at 100V. This is just 16% larger than the observed value; the difference is likely accounted for by the effects of fringing fields at the ends of each fingers.

The variation of generated force with displacement was investigated by using a capacitive force sensor (FemtoTools FT-S540) which was driven into the central plate of the MEMS device in steps of 100 nm using a motorised stage (PI M-112.1G). The gain of the sensor, and the relative stiffness of the sensor and MEMS were calibrated using a Nanoindentation Tester (CSM Instruments), and the measured results adjusted to reflect the fully blocked force of the MEMS actuator [8]. The measurements were taken with a voltage applied to the MEMS of $V_M = 50$ V, at a frequency of 5 kHz. Both the static and dynamic force was measured at each step in z in order to calculate the actual distance moved by the stage. The calibration was limited by the deflection range of the force sensor, however it is clear to see from the results in figure 6 that the actual increase in applied force is much less than predicted. This is due to the fact that when the central plate of the device is pushed into the substrate, it is the innermost electrodes, which happen to be the shortest within the design, that are displaced by the greatest amount, whereas
Figure 4: (Colour Online) Calculated potential for the geometry of the device, with the rotor coplanar with the stators (left) and depressed 20 µm below (right). The outline of the electrodes are indicated by the black lines.

Figure 5: (Colour online) Plot of the variation of net vertical force density calculated by FEA as a function of the vertical displacement of the comb finger (blue squares). The linear behaviour in the region of small displacements is indicated by the fitted pink line.

the longer comb fingers that are closer to the edges of the device are more closely anchored to the substrate.

4. Conclusion

The shaded area in figure 6 represents the accuracy to which it is possible to align the sample and MEMS within an actual piezoelectric measurement. The overall error on the force measurement was slightly increased to represent the small measured variation in force with displacement, in comparison to the accuracy to which the force can be measured with the FemtoTools sensor. However it is clear that the variation in generated force is much less than that predicted by the FEA, for the reason stated above. In fact it is not possible to push the central plate of the device much further towards the substrate without breaking the suspension beams, due to the stiffness and intrinsic stresses within the Ni thick films from which they are made. Further work is
required to re-design the flexural supporting beams to address this issue. Nonetheless from this analysis, provided the optical alignment is carefully carried out during the measurement, we can conclude that the force applied to the micro-scale piezoelectric sample is accurately quantified.

In summary, a MEMS device was produced for the evaluation of piezoelectric coefficients in micro-scale components. The force generated by the electrostatic comb drive actuator was characterised as a function of downwards displacement of the central suspended plate. Finite element analyses of the electric potential around a 2D cross section of the actuator electrodes were successfully used to predict the variation in levitation force. The models showed good correlation with the measured force with zero displacement. The increase in force with decreasing $z$ was found to be smaller than the variation predicted by the models, due to the fact that not all the electrodes are displaced by equal amounts due to the flexural supporting beams of the device which attach the comb fingers to the MEMS substrate.

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