Capacitance variation in electrostatic energy harvester with conductive droplet moving on electret film

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Abstract. This work addresses numerical finite element calculations on a droplet-based electrostatic energy harvester to reveal additional characteristics that supplement previous test results. Assumptions of 2D electrode and static droplet profile have been applied to make the simulation achievable based on the real prototype. We investigate the consequences of a uniform space charge distribution in the film. Capacitance variation and open-circuit voltage of the simulation model have been determined and display respectively maximum and minimum magnitudes when the droplet is in the middle of finger gap. The sharp variation of capacitance, during which the droplet moves from the gap centre to the finger centre, can explain the narrow peaks of output voltage seen in experiments. Additionally, the influence of droplet size on the capacitance variation is also investigated.

1. Introduction
Harvesting energy from the environment and converting to electric energy has been a hot spot in both scientific and engineering fields since last two decades [1]. Various energy conversion principles, such as electromagnetic, thermoelectric, piezoelectric, and electrostatic, etc., have been explored [2]. Electrostatic energy harvesters, which mainly operate on the capacitance variation, and mostly employ a mass-spring configuration, have attracted considerable attention due to their compatibility with microfabrication process. Distinguished from the conventional mass-spring configuration, the electrostatic energy harvester utilizing droplet or liquid flow has advantages for low frequency non-resonant operation [3-7].

A fluidic electrostatic energy harvester utilizing interdigital electrodes (IDEs) and a thin, charged dielectric film was demonstrated in our previous work [8]. It operates on a rolling conductive droplet causing variations in the capacitance and open-circuit potential of the device’s electrical port, and thereby converting mechanical energy into electrical energy when a load is connected. The detailed experimental characterization supported by a phenomenological lumped model was performed with the prototype and is presented in [9]. However, due to lack of available experimental data on the distribution of fixed charges in the film and on the possible deformation of the droplet in the inhomogeneous electric field, as well as the serious obstacles to analytical treatment of the electrostatics in the complicated structure, essential details that would be useful for further developments are not known.

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To provide better understanding of this type of device, we investigate the droplet-based energy harvester concept by finite element analysis (FEA), so as to extract more features of this type of energy harvester that can’t be obtained from the experimental results directly.

2. Modelling and simulation method

2.1. Model description

The droplet based electrostatic energy harvester (as shown in Figure 1a) can be modelled by a simple equivalent circuit (Figure 1b). The embedded charges inside the thin insulation film give rise to the voltage source $V_e$, while the resultant capacitance from the two terminals of the interdigital electrodes involving the conductive droplet can be simplified as a variable capacitance. Thus the relation between the embedded potential and the terminal potential can be expressed by,

$$V_{\text{out}}(x) = V_e(x) + \frac{Q(x)}{C(x)}$$  \hspace{1cm} (1)

As the droplet moves across the thin film, the resultant capacitance varies in pace with the droplet displacement with respect to IDE fingers.

![Figure 1. Droplet-based electrostatic energy harvester. (a) Optical photo of prototype; (b) Equivalent circuit characterizing the energy harvester.](image)

2.2. Simplifying assumptions

The device has greatly varying length scales within it, posing serious challenges for FEA meshing, i.e. 100nm metal film thickness, micrometre scale film thickness, millimetre scale of droplet/electrode pattern and centimetre scale device dimensions. With the technical difficulties of meshing considered, the following assumptions were applied in the model to make FEA achievable:

- the IDE finger is treated as 2D structure with zero thickness;
- the variation of droplet profile due to the droplet dynamics or electrostatic forces has been neglected;
- and the droplet is simplified as a spherical cap with a circle contact area on the dielectric film.

As the thickness of IDE finger is rather small compared with the thickness of insulation film, the 2D model can reduce the meshing difficulty but without losing the transducing feature of IDE. And the simplifications on the droplet profile actually characterize a static droplet, without addressing the dynamic behaviour. Therefore, these assumptions are reasonable. In addition, the charge distribution in the thin film is not known. As a first investigation we therefore consider a uniform space charge density and investigate its consequences.

2.3. Simulation domain

The simulation domain is depicted in Figure 2. The droplet was treated as a conductor and PTFE was used as the insulation film. The detailed geometrical parameters are listed in Table 1.
Table 1. Parameters of the simulation domain.

| Parameters                  | Unit | Value |
|-----------------------------|------|-------|
| Finger width of IDE         | µm   | 400   |
| Finger gap of IDE           | µm   | 400   |
| Number of finger pair       | –    | 10    |
| Droplet size                | µm   | 1200  |
| Insulation film thickness   | µm   | 2     |
| Glass substrate thickness   | µm   | 400   |
| Thickness of air domain     | µm   | 2000  |

The calculation was conducted by the MEMS module of the commercial software COMSOL Ver. 4.3. Charge conservation was set for the whole simulation domain with 0-V boundary on the outer surface of the domain and also on the bottom surface of the glass substrate so as to match with practical testing where the device was placed on a conducting surface. In order to obtain the capacitance variation with respect to the droplet displacement, a particular fine mesh was generated for IDE fingers and the thin film, as illustrated in Figure 3. As an aid in the difficult meshing of the thin film structure, virtual surfaces were used to control the mesh generation.
While the droplet moves along the central axis (x-direction) of the simulation domain, the capacitance was determined by applying 1.0V and 0V on the two terminals (A and B), respectively. The variation of the open-circuit potential of the prototype was checked by setting terminal A to zero charge while keeping terminal B grounded. Finally, the short-circuit charges on each electrode were checked by setting both to ground. A uniform space charge density was arbitrarily set at -1.0 C/m³ for the insulation film. This is meaningful as the electrostatics is linear and only a scaling is necessary to correct the result to another value of embedded charge.

3. Results and discussion

3.1. Capacitance variation and open-circuit voltage

Figure 4 and Figure 5 plot the variations of the capacitance and open-circuit voltage with respect to the droplet position, respectively. It is noted that the maximum values occur at the positions where the droplet is right in the middle of the two adjacent fingers (gap center) while the minimums are corresponding to the positions where the droplet are sitting right on the top of one finger (finger center). Moreover, the capacitance varies sharply as the droplet moves from the gap center towards the finger centre, which can explain why the narrowly peaked output voltage appears in the test results [9].

According to Figure 4, the range of capacitance variation in the energy harvester is not so impressive for a droplet having a diameter of 1.20 mm, less than 0.2 pF. For the real prototype, the thickness of insulation layer was smaller, down towards 1.0 micron, thus the capacitance variation is larger.

3.2. Charge variation on the grounded electrodes

Figure 6 plots the charge distribution on the two terminals under grounded condition with the droplet moving within one period (four times of finger width) of IDE configuration. Due to computational errors, there are considerable fluctuations in the result. The reason for the small variations, in the third decimal, is cancellation which can be verified by calculating short-circuit charge as the product of the results in figures 4 and 5 and gives a variation that drowns in numerical error (not shown). The peak in the open circuit potential of figure 4 is a notch in its magnitude that nearly cancels the corresponding peak in the capacitance. However, figure 6 still indicates some tendency of the charge variation with respect to the droplet position: the charge variations on the two terminals alternate and reach nearly the same value at the positions when the droplet is at the gap centre. This is also where the change is largest which would give peaks in the derivative of the short-circuit charge that alternate with the period shown in the experiments. Therefore, a uniform charge distribution in the film seems to be able to qualitatively account for the observed behaviour, but numerical accuracy needs improvement to make a quantitative test.
3.3. Influence of droplet size on the capacitance variation

The influence of droplet size upon the capacitance is plotted in Figure 7, in which the droplets hold a constant contact angle of 60º with both positions at gap centre (gc) and finger centre (fc). It is clear that for the IDE with finger/gap width of 400µm ($C_0=6.09pF$), the total capacitance variation ($\Delta C=C_{gc}-C_{fc}$) increases rapidly with the droplet size, and has a maximum of 1.4pF for a droplet size of 2.5mm. The variation drops as the droplet size keep increasing, even turns to negative when the droplet covers more than one pair of fingers. This indicates that the droplet size should be matched well to the IDE pitch and could favourably have been considerable larger than what was used in the previous experiments. The finding explains why a bigger droplet gave larger output in test [9].

4. Conclusions

Based on a previous prototype of a droplet-based energy harvester, a FEA model was built by adopting several simplifying assumptions. Numerical calculations were used to obtain variations of capacitance, open-circuit voltage and short-circuit charge by setting different boundary conditions. The findings are qualitatively consistent with the voltage peaks related to the short-circuit charge in previous tests. The numerical accuracy of the short-circuit charge needs improvement for performance estimates. It is of interest to further study the effect of charge variations in the film. It is also found that droplet size should match with IDE pitch to have a larger capacitance variation.

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