A PRELIMINARY STUDY OF AN ELECTROSTATIC CURVED BEAM ACTUATOR FOR A BIO-MEMS FORCE SENSOR

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ABSTRACT

An electrostatic curved beam microactuator embedded in a microfluidic device meant to be a probe to measure the mechanical properties of biological cells is modeled, fabricated, and evaluated. Our study in aqueous media showed that an actuation voltage of 8 V is sufficient to generate an intended force of up to 97 μN and achieve a static displacement of up to 9.7 μm - these values demonstrate that we should be able to deform a cell with the appropriate force and deformation strain.

INTRODUCTION

Electrostatic curved actuators are known to achieve large displacement and large force compared to comb drives and parallel plates for a given geometric footprint and fixed actuation voltage [1], [2]. This makes them a suitable candidate for force generation where actuation voltages are constrained to be low, such as in an aqueous environment where hydrolysis limits actuation voltage to a range of ± 8 V. The actuator is designed to be used as a probe to measure the mechanical properties of cells as they transit through a microfluidic network [3], [4].

THEORY

The curved actuator comprises of three main components: beam electrode, set of curved electrodes, and an insulator film (Fig. 1). The curved electrodes are rigid while the beam electrode is a compliant structure with both ends clamped to anchors. The beam and curved electrodes are immersed in a dielectric medium. Upon the application of a voltage to the electrodes, the beam electrode zips into the curved electrodes. The insulator film on the electrodes prevents electric shorting during the zipping process.

Deflection profiles as a function of voltage are predicted using the *Rayleigh-Ritz* method [5] applied to a first-principles model of the actuator. The electrode gap (Fig. 2), out of plane deflections, and fringe field effects are neglected for simplicity. Since the actuator is symmetric about the line of symmetry, only the left-half portion of the actuator is modeled by employing a symmetry condition. In the model, a trial function for displacement w_L is assumed in terms of electrode geometry and unknown quantities. The unknown quantities are solved by minimizing the actuator's total potential energy π defined by Equation (1) with respect to the unknown quantities using MATLAB® function minimization solver *fmincon*.

$$\pi = U_s + U_{el} + U_M \quad (1)$$

In Equation (1), U_s is spring energy, U_{el} is electrostatic potential energy, and U_M is the moment work by the right-half portion of the actuator. Upon solving the unknown quantities, the static displacement and beam electrode shape function are determined. Critical actuator dimensions are given in Table 1.

EXPERIMENT

To validate deflection predictions, we fabricated the curved actuator from a silicon-on-glass wafer using standard lithographic micromachining methods. For our experiments, the actuator is submerged in deionized water and a square wave at 500 kHz with a

pulse height of a variable $\bar{V}$ is applied. Displacement w_L is measured using an inverted microscope equipped with a camera and image processing software.

RESULTS AND CONCLUSION

The experiment and model predictions are in good agreement despite using the simplifying assumption that the electrode gap is zero (Fig. 3). This simplifying assumption causes the model to overpredict displacement at low voltages, where the finite electrode gap required for fabrication ($\sim 2.5 \mu\text{m}$) causes the moving beam to be not fully zipped in and thus a lower actuation force is applied (Fig. 4). The idealized zipping motion as a function of voltage is shown in Fig. 5. Experimental results in an aqueous media demonstrate that a voltage $\bar{V} = 8$ V is sufficient to generate an intended force of 97 μN and achieve a displacement of 9.7 μm (Fig. 3) - these values demonstrate that we should be able to deform a cell with the appropriate force and deformation strain. Future work will study the dynamic behavior of this actuator and use the actuator to probe cell mechanical properties by pairing the actuator with a sensor unit.

Figure 1: (A) Schematic of the curved actuator in the unenergized and energized states. (B) SEM image of the actuator.

Figure 2: Schematic of the left half of the actuator in the energized state. The beam electrode is seen partly zipped into the curved electrode with displacement w_L . Here, M designates the moment or torque by right half of the actuator on the left half.

Figure 3: Static displacement in an aqueous environment. There is a good match between experiment and model for higher voltages. However, the model is less accurate at low voltages because the simplified model omits a gap between the actuators at the base of the beam, which is required to electrically isolate the two electrodes.

Figure 4: Experiment images demonstrating the actuator zipping action for square wave at 500 kHz with different voltage amplitudes (A) $\bar{V} = 0$, (B) $\bar{V} = 6$, and (C) $\bar{V} = 8$ V, respectively. As voltage $\bar{V}$ is increased the zipping length increases and the initial unzipped length decreases.

Figure 5: Prediction of the actuator zipping as the actuation voltage $\bar{V}$ is increased. The solid black line is the curved actuator profile $s(x)$, the dashed lines are the beam electrode deflection profiles at different voltages $\bar{V}$.

Table 1: Actuator model parameters

Parameter (unit)	Numerical value
Beam electrode half-length (μm)	1000
Beam electrode height (μm)	45
Beam electrode thickness (μm)	6
Insulator film thickness (nm)	20
Reinforcing beam stiffness (N/m)	5
Dielectric constant of insulator film	9
Beam material Young's modulus (GPa)	130
Dielectric constant of deionized water	78

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