Non-Linear springs for Enhancing the Functionality of Electrostatic Actuators

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Gap-closing electrostatic actuators are inherently nonlinear and their dynamic range is often limited by the pull-in instability [1]. To overcome this, for the first time ever, we propose a nonlinear spring that counteracts the nonlinear effects of electrostatic attraction. The nonlinear spring is designed to extend the stable response of the actuator to a full range, and to enforce a linear electromechanical response. We present a method for designing elastic springs with monotonically increasing stiffness. The mechanism we propose is effective shortening of a straight clamped-guided beam flexure, by wrapping it over a cam [2]. To validate our concept, we have designed and measured the response of a nonlinear spring with a prescribed force-displacement law. Experimental measurements of a macro-scale spring are in good agreement with the model predictions.

The classic gap-closing parallel-plates electromechanical actuator is schematically illustrated in Fig. 1a, and its non-linear electromechanical response is plotted in Fig. 1b. The parallel-plates actuator consists of a mobile electrode (rotor) suspended on a linear elastic spring above a stationary electrode (stator). One of the electrodes is grounded and the other is subjected to a constant voltage. The non-linear equilibrium curve of this system includes a stable branch (solid line in Fig. 1b) and an unstable branch (dashed line).

The peak voltage for which equilibrium still occurs is the pull-in voltage, and at this limit point the stability of the system becomes critical. In some switching applications the pull-in instability is a beneficial feature of the electromechanical response, but in many applications the limited stable range and the non-linear nature of the stable response are detrimental for optimal functionality.

To this end, we analytically derived the functional form of the force-displacement law of a mechanical spring, which would ensure a linear response of the parallel-plates actuator. The stiffness
of the required spring is initially zero, and it monotonically increases as the displacement increases. It is impractical to implement such a spring because it requires a vanishingly small initial stiffness.

Figure 2: Voltage-displacement law of a parallel-plates actuator with our new non-linear spring. Beyond the pre-load, the response is linear and a full range of displacement is achieved

Therefore, we design the spring such that during an initial pre-load process, the spring has a constant stiffness and the parallel-plates actuator follows the classic nonlinear stable response. Beyond this pre-load the electromechanical response of the actuator becomes linear (Fig. 2).

A macro-scale model of the non-linear spring, constructed from cantilever beams with a guided edge condition was fabricated and tested (Fig. 3). Figure 4 presents the measured force-displacement response (solid line) and the predicted response (dashed line). We consider the good agreement between the measurements and our predictions as validation of our concept for designing non-linear springs.

Micro-scale test devices for validating the response of gap-closing parallel-plates actuators with linear response are currently in production.

References