A HIGH DYNAMIC RESTORING FORCE ELECTROSTATIC ACTUATOR

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ABSTRACT

A surface-micromachined parallel-plate MEMS actuator has been fabricated using a modified version of the Texas Instruments Inc. Digital Micromirror Device fabrication process. The actuator employs a unique dynamic restoring force mechanism to overcome stiction and electrostatic hold-down issues commonly faced by surface micromachined actuators. This dynamic boost results in a ~16x increase in restoring force and a ~4x increase in the voltage required to hold the actuator down compared with static actuation, without affecting the device's initial pull-in voltage. Furthermore, the actuator utilizes a torsion architecture that greatly reduces contact area and electrostatic field strength, thereby further reducing stiction.

INTRODUCTION

Stiction is one of the biggest reliability challenges in surface micromachined electrostatic contact actuators [1,2]. This challenge is often compounded by the desire to maintain a continuous voltage waveform on the device. Depending on the application, this waveform could serve different purposes. For example, in sensor applications the waveform could be used to sense the position of the moving element. Alternatively, in a micro-mechanical relay, the waveform would be the signal that the device is switching on and off. Regardless of the application, any waveform across the actuator provides its own electrostatic attraction force which can prevent the release of the moving plate when it is landed, creating an unwanted electrostatic hold-down effect.

Both stiction and electrostatic holding force create a need for high spring restoring force. Spring suspensions must be made stiff enough to overcome unwanted forces that are holding the actuator in the closed position. The tradeoff is that stiff suspensions need high amounts of electrostatic force to actuate in the first place, which translates to high actuation voltages and large actuation electrodes. High voltages can create a number of additional challenges, including dielectric breakdown, dielectric charging, arcing, etc [3]. These problems can be alleviated with techniques such as waveform shaping or constant charge biasing [4], in which the high voltages are used only to initiate actuation and are backed down as the structure lands. However, high voltage supplies are generally not available in most MEMS end-applications and must be supplied by SoC or SiP integrated DC-DC converters, which may place practical limitations on the voltage available. Large actuation electrodes can cause fabrication and die area concerns, and they may result in increased stiction due to large surface contact area [1].

To circumvent these challenges, this paper presents an actuation mechanism that dynamically increases spring restoring force without increasing the force needed to actuate the device.

THEORY

According to basic parallel plate actuator analysis, the electrostatic force F_e between two parallel plates with overlap area A resulting from an applied voltage V is

$$F_e = \frac{\epsilon A V^2}{2(x_0 - x)^2} \quad (1)$$

where x_0 is the initial gap between the plates and x is the displacement. As the actuator approaches the closed state and the gap $(x_0 - x)$ becomes small, the electrostatic force becomes quite large. However, when the force is applied to a linear restoring spring F_s , the electrostatic force overwhelms the spring and device “pulls in” when the displacement is a third of the initial gap, at voltage

$$V_{PI} = \sqrt{\frac{8kx_0^3}{27\epsilon A}} \quad (2)$$

From equations (1) and (2), it is easy to see that for a given pull-in voltage, the amount of electrostatic force that exists when the actuator is in the closed position far exceeds the spring restoring force in the closed position. This excess electrostatic force is effectively “wasted” because it does not serve to oppose a restoring force that will help release the actuator from a contact surface.

$$F_{wasted} = F_e(V_{PI}, x_{closed}) - F_s(x_{closed}) \quad (3)$$

In a simple example, if we assume air dielectric and further assume that the closed position is $1/10^{\text{th}}$ the initial gap and voltage is just above V_{PI} , the electrostatic force in the closed position is ~16 times larger than the spring restoring force.

Ideally this “wasted” force could be recovered by using it to do some useful work, i.e. compress a secondary stiff spring that does not engage until the actuator is nearly closed. However, the amount of energy stored in this hypothetical secondary spring is proportional to the displacement of that spring, so to maximize energy the secondary spring should engage rather early (but after pull-in). However, the spring will then release its energy over its entire range of travel. Since both stiction and electrostatic holding forces are strongest over very small distances, it would be more effective if the secondary spring were to release its energy all at once. This would provide a strong impulse to the moving plate and effectively “knock” it off of the surface on which it was landed. The following section describes a design that accomplishes this goal.

DESIGN AND FABRICATION

The actuator consists of a metal superstructure suspended above a set of stationary electrodes with torsion and cantilevered springs (Fig. 1a). The superstructure is partitioned into three sections: two paddles and a center plate. The paddles both rotate inwards on a set of torsion springs, while the center plate between the paddles remains parallel to the substrate and eventually lands on the SENSE electrode beneath it. A thin dielectric layer coats all underlying electrodes to prevent shorting.

Figure 1: Top view SEM image and side view schematic diagrams are aligned and approximately to scale with each other in the x-axis. (a) SEM image of fabricated actuator with major design features labeled above the image and electrode names labeled below the image. (b) DC potential is applied to DRIVE electrode, center plate moves downward. (c) Inner torsion springs store energy. Center plate lands on SENSE electrode. (d) Paddles continue to rotate until they hit the hard stops. Inner torsion spring relaxes, transfers energy to over-rotation spring. (e) Voltage is removed from DRIVE. Paddles bounce upward, simultaneously loading over-rotation and inner torsion springs. Upward force is transferred to center plate to overcome stiction and electrostatic hold-down forces.

The actuator is fabricated with a modified version of the Digital Micromirror Device (DMD) process described in [5], with the second sacrificial spacer and mirror metal levels removed. This process produces two thicknesses in the superstructure metal: a thick layer that has been previously described in literature as the “yoke”, and a thin layer known as “hinge”. The “yoke” layer is used in this design to create the rigid plates that form the paddles and the center plate, as well as the stiff over-rotation springs. Both the paddles and the center plate are further stiffened by a corrugation pattern that can readily be seen in Fig 1a. The “hinge” layer is used to create the more compliant torsion springs and cantilevered springs.

The device operates as follows: A bias is placed on the DRIVE electrodes beneath the paddles, creating an electrostatic force that causes the paddles to rotate inwards (Fig. 1b). Energy is stored in the outer torsion springs, the cantilevered springs, the over-rotations springs, and inner torsion springs. The ratio of the energy stored in the over-rotation spring vs. the inner torsion spring depends on the ratio of their stiffnesses. The inner torsion spring is much more compliant than the over-rotation spring, so it stores a majority of the energy. The role of the cantilevered springs is simply to increase overall restoring force.

Once the center plate lands on the SENSE electrode, the paddles continue to rotate (Fig. 1c), producing so-called “over-rotation”. This causes the inner torsion spring to relax and transfer energy to the over-rotation spring. The paddles continue to over-rotate until the hard stops on paddles land on the GND electrodes that flank the SENSE electrode, producing a stable down-state or closed position (Fig. 1d). Assuming the over-rotation spring is linear, its potential energy is given by

$$U_{OR} = \frac{1}{2} k x_{OR}^2 \quad (4)$$

The over-rotation springs are stiff so their spring constant k is high, and they are also quite long which means that over-rotation travel distance x_{OR} adds substantially to the paddles’ overall travel x_{closed} . As such, the over-rotation step significantly increases the total potential energy stored, as shown schematically in Fig. 2. However, since the center plate has already landed before over-rotation even begins, this additional energy storage does not affect the pull-in voltage of the device. The high electrostatic force of the parallel plate in the closed position is simply used to do additional work, rather than being “wasted”.

Figure 2: Schematic diagram of stored energy in the various states referenced in Fig. 1.

Upon release, voltage is removed from the DRIVE electrodes with a sharp slew rate. The paddles bounce upwards, and potential energy stored in the springs is converted to kinetic energy in the paddles. Meanwhile, the center plate may remain stuck down due to electrostatic hold-down forces and stiction (Fig. 1e). As a result, both the over-rotation and torsion springs become loaded, but the

over-rotation spring deflects in the opposite direction than it does when it lands. This temporarily results in a negative potential energy with respect to equilibrium (Fig. 2) since both springs cannot be simultaneously loaded in equilibrium. Upward force is transferred to the center plate to overcome electrostatic hold-down and stiction, which both operate over small distances.

The combination of the over-rotation springs and the inner torsion springs essentially produces a stiffer spring constant during release than it does during landing. This effect occurs because during the landing over-rotation step, the inner torsion springs relax, which softens the combined spring constant, while during release the inner torsion spring become loaded, which stiffens the combined spring constant. The result is a greater upward impulse delivered to the center plate to “knock” it off the surface on which it was landed.

One of the consequences of this release mechanism is that over-rotation spring will ring and the center plate and paddles will oscillate with respect to each other on their way up. This is an acceptable tradeoff because once the center plate is released off the surface, it is not subject to stiction forces and the electrostatic hold forces diminish rapidly. Thus, the ringing should not cause the center plate to re-land, and it should damp out due to air and anchor damping.

RESULTS

Figure 3 shows a normalized land and release C-V plot for a parallel array of fabricated actuators. The array is pulled-in at $DRIVE \approx 35V$. This values match well with Coventorware® FEA simulations after accounting for intrinsic metal stresses. Note that there is less than 1V of hysteresis between the land and release curves, evidence that the amount of “wasted” electrostatic force in the landed state has been minimized. This is not only a result of the over-rotation mechanism, but also because the non-parallel relationship between the rotating paddles and the DRIVE electrodes means that the electrostatic force does not grow as quickly with displacement as it would with a parallel plate drive that obeys equation 1.

Figure 3: Normalized C-V plot for an array of actuators. Capacitance is measured on the SENSE electrode. Actuation voltage is applied on the DRIVE electrodes.

FEA simulations also confirm that the effective combined spring constant for the inner torsion and over-rotation springs is

greater when the device is releasing than when the device is landing. Figure 4 shows a stress profile of a quarter-model in the landed state, illustrating the distribution of energy stored in each of different springs.

Figure 4: Mises stress profile of a 3D quarter-model actuator in the landed position, simulated with Coventorware® FEA software. Z-axis displacement is exaggerated 10x.

Both static and dynamic hold-down voltages were measured by placing a voltage on the SENSE electrode and attempting to release the actuator. Dynamic electrostatic hold-down voltage is 20V and is measured with a DRIVE waveform fall time of <100ns (Fig. 5). This is 4x greater than the static hold-down voltage of 5V, measured with a slow fall time, indicating that the dynamic release mechanism is functioning properly. Equation 1 implies that a 4x increase in hold-down voltage results from a 16x increase in restoring force.

Figure 5: Static electrostatic hold down (5V) and dynamic hold down (20V) plots. Voltage is applied to the SENSE electrode in the down state, the varactor is released, and C is measured. In the dynamic test, the switching waveform on the DRIVE electrode has a fall time of <100ns, while in the static test it is much slower.

Optical measurement of actuator dynamics was taken with a Polytec laser Doppler vibrometer to further verify the over-rotation mechanism. Figure 6 shows displacement vs. time for a point in the center of the center plate and a point on the inner edge of the paddle while the actuator is landing. As expected, once the actuator begins traveling downwards, the displacement of the center plate is slightly greater than that of the paddle edge. Once the center plate makes initial contact with the SENSE electrode (Fig. 6, time a), the paddle continues to over rotate until it hits a hard stop, pulling the center plate flatter and into more intimate contact with the SENSE electrode. After the hard stop is reached (Fig. 6, time b), there are some minor oscillations between the paddles and the center plate that die down within 50ns.

Figure 6: Displacement vs. time of center plate and inner edge of paddle, measured with a laser Doppler vibrometer. The center plate makes initial contact with the SENSE electrode at time (a), while the paddle continues to rotate until it hits a hard stop at time(b).

Also, since the actuator paddles never touch the DRIVE electrodes, contact area under high field is greatly reduced, further reducing stiction. Actuators with this torsion architecture survived room temperature life-test in which the DRIVE voltage was cycled for 5 billion cycles without any observed stiction failures.

CONCLUSION

A novel surface-micromachined electrostatic parallel plate actuator has been designed and fabricated. The actuator has been shown to require 4x higher voltage to hold it down under dynamic release conditions than static release. This is a result of a unique over-rotation mechanism that allows the actuator to capture, store, and release more actuation energy without affecting its initial pull-in voltage. The extra restoring force is especially useful in applications where stiction and electrostatic holding forces pose a significant challenge, such as micromechanical relays and sensors.

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