A DC-POWERED, TUNABLE, FULLY MECHANICAL OSCILLATOR USING IN-PLANE ELECTROTHERMAL ACTUATION

Kabir Udeshi[1] and Yogesh B. Gianchandani
Engineering Research Center on Wireless Integrated Microsystems
University of Michigan, Ann Arbor, USA

ABSTRACT

This paper describes a fully mechanical micromachined oscillator that is driven using only a DC power source. The oscillator is made using an electrothermal actuator, that when actuated, opens a switch to cut off its supply current. Two versions of this oscillator have been designed using distinct hysteresis mechanisms: one structural, and the other thermal. The devices have 30 μm thick electroplated copper structures and 3 μm minimum features, fabricated using a single mask low temperature UV-LIGA process, with a footprint of 1 mm x 1 mm. Measured results confirm the operation and show that the oscillators are capable of generating a tunable signal with a frequency range from 38 Hz to 1200 Hz and a duty cycle between 0.3 and 0.7, while requiring an operating voltage less than 0.5 V. The maximum power consumption is 180 mW.

I. INTRODUCTION

Oscillators generate a modulating signal from a DC power source and are used in all applications that require periodic excitation. A wide spectrum of micromachined devices ranging from strain and pressure sensors [1] to accelerometers and gyroscopes [2,3] either require or exhibit improved performance when driven by a modulating signal.

On-chip signal generators reported in the past needed electronic components for their operation. The implementation of these oscillators using standard microelectronic circuits severely limits their voltage and power handling capacity and makes them unsuitable for direct use in any application demanding even moderately high voltages or power levels. Even oscillators that have utilized MEMS components have all used electronics to provide feedback of an amplified signal. Micromachined mass-spring systems have been used to replace LC tank circuits to provide frequency selective feedback [4]. In other cases, MEMS-based variable capacitors have been used to make voltage controlled tunable oscillators [5].

This paper describes a *fully mechanical* micromachined oscillator that can be operated using a single DC power source, without the aid of any electronic components. To our best knowledge, this is the first implementation of a micro-scale mechanical oscillator. The first section describes the device concept and operation of the oscillator that has been implemented in two configurations, each of which occupy less than 1 mm^2. The next section describes the design, modeling and fabrication of the oscillator. Finally, measurement results validate the operation of the oscillator over a range of frequencies and duty cycles.

II. DEVICE CONCEPT & OPERATION

The oscillator is created by using an electrothermal actuator [6], that when actuated, opens a normally closed switch, thereby cutting its own supply current. Subsequent cooling of the actuator results in the closure of the switch and causes the cycle to repeat, resulting in oscillations. In order to keep the switch open or closed for a controllable duration of time, hysteresis must be present in the system. This hysteresis allows the system to remain in unstable equilibrium for a predefined amount of time. The oscillator has been implemented in two configurations, Type I and Type II, using different hysteresis mechanisms.

Before the oscillator can be operated, it must be primed once to make a normally closed switch as the switch is fabricated with its contact plates apart. Figure 1 shows the priming operation. Electrothermal actuator *A* is used to push the switch into a closed position and compresses spring *B*. Once the switch is in the closed position, a latch is automatically engaged, clamping the switch closed permanently.

In the Type I device, hysteresis is incorporated using a bistable toggle mechanism [7]. If the force applied on the toggle is gradually increased, the structure snaps from its original mode to a snapped mode at the upper bifurcation point, which is observed as a sudden increase in

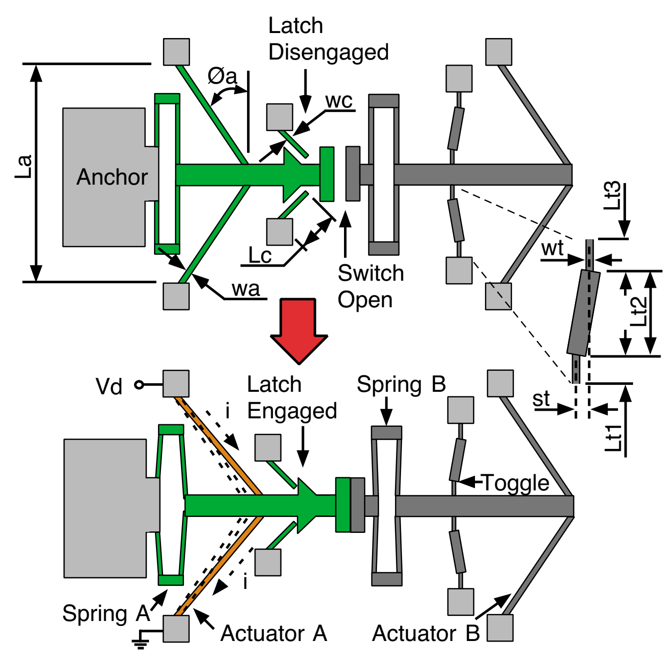

Fig. 1: Device configuration as fabricated (top), and after priming. Priming is permanent, and achieved by driving actuator *A*.

[1] Address: 1301 Beal Ave., Ann Arbor, MI 48109-2122, USA; E-mail: kudeshi@umich.edu

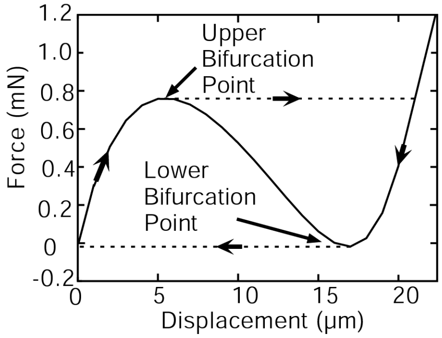

Fig. 2: FEA load-displacement response of the bistable toggle element.

displacement (Fig. 2). A similar sudden decrease in displacement is observed at the lower bifurcation point if the applied force is quasi-statically decreased. When deployed, the oscillator cycles between the two states as shown in Fig 3. In the initial state, the switch is closed and the thermal actuator is un-deflected. When the supply voltage is turned on, current flows through the switch, heats up the thermal actuator and applies an increasing force on the toggle. Once the actuation force exceeds the force corresponding to the upper bifurcation point of the toggle, the device snaps through, generating a large displacement, opening the switch and cutting the current to the actuator. The device is now in its deflected state. Since no power is supplied to the actuator, it cools down due to heat dissipation to the substrate, decreasing the force applied on the toggle. The toggle snaps back to its original position when the applied force falls below that of the lower bifurcation point, closing the switch and restoring the current to the actuator. The device thus returns to its initial state, permitting the cycle to be repeated.

In the Type II oscillator, the function of bistable element is carried out by the intrinsic thermal hysteresis of actuator B, which is caused by the duration of heating and cooling

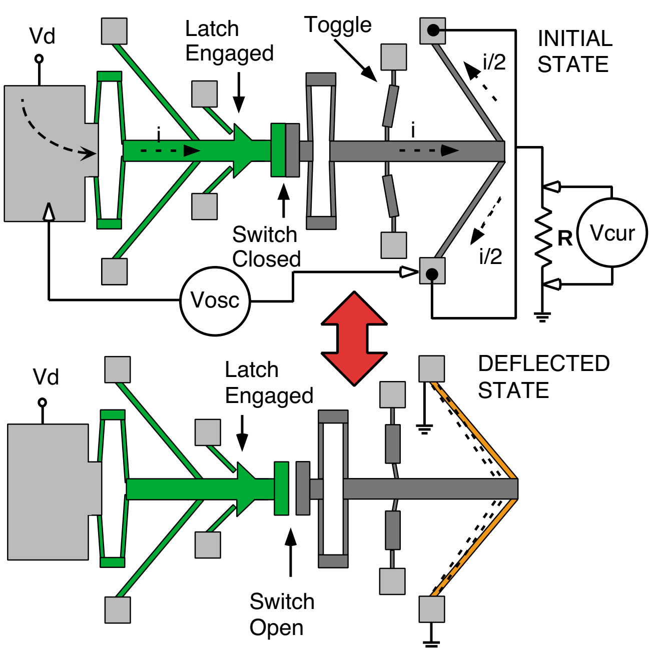

Fig. 3: Device operation: current flow when switch is closed (top) causes displacement of electrothermal actuator (bottom), opening the switch. Subsequent cooling of the actuator closes the switch, permitting repetition.

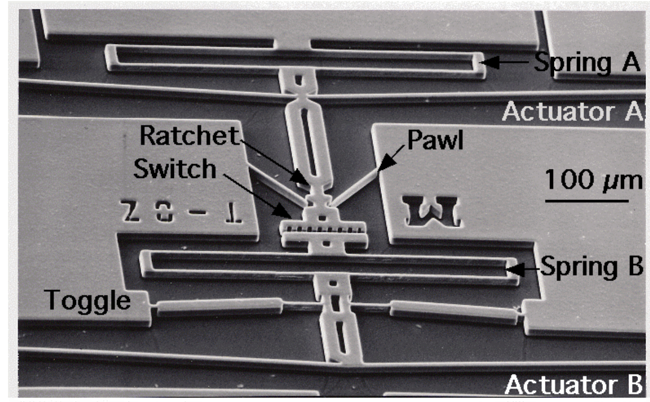

Fig. 4: SEM image of fabricated oscillator.

time constants of an electrothermal actuator. It will be shown through experimental results that a higher frequency of oscillation can be obtained using thermal hysteresis, due to the smaller hysteresis loop. In this version of the device, spring B is eliminated.

III. DESIGN & FABRICATION

The elements designed include the latch mechanism for the normally closed switch, the bistable toggle mechanism, spring elements, and electrothermal actuators.

The concept of the latch is derived from that of a pawl and ratchet mechanism, which permits rotational motion only in one direction. In this case, linear motion is permitted only in one direction. The pawl is made from a cantilever beam whose axis of deflection is at an angle θc to the direction of motion of the ratchet. By carrying out a free body analysis it may be proved, that the stiffness of the pawl while being pushed in the forward direction of motion of actuator A, is $Cos^2(\theta c)$ times the stiffness in the reverse direction of motion. Thus if actuator A is displaced far enough so that the pawl can click into position behind the ratchet tooth, the assembly is latched. The latch was designed so that once engaged, it limits the reverse motion of the ratchet to 2 μm, hence creating a normally closed switch with a compressive force on the contact plates.

The design of the bistable mechanism is carried out using FEA. Figure 2 shows the force displacement response of the bistable toggle mechanism obtained from a nonlinear analysis of the structure using two dimensional beam elements considering large displacements. Actuators A and B were designed so that they would provide sufficient forces using DC excitation to overcome the opposing force exerted by the latching mechanism and toggle respectively. The force-displacement characteristics of the actuators were obtained using the following to get maximum displacement and force $(Dmax, Fmax)$ assuming a uniform increase in temperature (ΔT) of 600ºC [8]:

$$D\max = \frac{\alpha \cdot \Delta T \cdot \sin\Phi a \cdot \left(\frac{A}{6 \cdot La} - \frac{8 \cdot I}{La^3}\right)}{\frac{16 \cdot I}{La^3} \cdot \cos\Phi a + \frac{A}{3 \cdot La} \cdot \sin\Phi a \cdot \cos\Phi a}; \quad \frac{F\max}{D\max} = \frac{2 \cdot \sin^2\Phi a \cdot A \cdot E}{La} \qquad (1)$$

where La and Φa are actuator dimensions as shown in Fig 1, I is the moment of inertia, A the cross-sectional area of the actuator and E the Young's modulus of the actuator material.

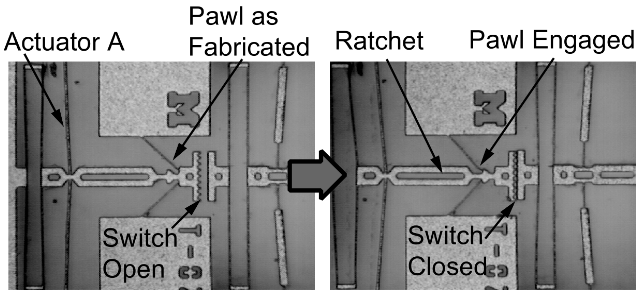

Fig. 5: As fabricated (left), the switch is open. During priming, electrical pulsing of Actuator *A* pushes the ratchet forward and engages the pawl (right) to make a normally closed switch.

The oscillator was fabricated using a single mask UV-LIGA process using SU-8 resist [9]. Thirty micron thick structures were fabricated from electroplated copper with a minimum feature size of 3 μm. A SEM of the oscillator is shown in Fig 4. Table 1 lists the dimensions of the fabricated device as marked in Fig 1.

IV. MEASUREMENT RESULTS

The experimental validation of the oscillator included testing the latching mechanism, capturing the hysteresis of the toggle mechanism and verifying the operation of the oscillator.

Pulsed power, which is favored for metal actuators [10], was used to prime the oscillator. Figure 5 shows optical micrographs of the priming operation. Initially the switch is open and the contact plates are separated. By applying a pulse of power to the thermal actuator *A*, the ratchet is pushed forward, overcoming the deflecting force of the pawl, closing the switch, and is locked into position by the pawl and ratchet mechanism. The switch was latched into position using an actuation voltage of 0.175 V, while drawing 150 mW of power for a period of 50 ms.

Figure 6 shows the measured displacement characteristics of the toggle mechanism obtained by cycling DC power applied to the electrothermal actuator *B*. While increasing input power to actuator *B*, the toggle is unresponsive until a threshold of about 1.5 mW, corresponding to the upper bifurcation point, is surpassed. Similarly, as the power level is decreased from 7 mW, the displacement follows the increasing power curve to about 3 mW, then deviates from it and falls sharply at 2 mW, which corresponds to the lower bifurcation point. The deviation of the measured response from the FEA results is due to the observed twisting of the toggle, as well as structural and material non-idealities.

Once the oscillator is primed, a DC voltage, Vd, is applied across the oscillator and powers actuator *B* (Fig 3). The power supplied to the actuator results in sustained oscillations, which are evident in visual observations as well

Table 1: Device Dimensions

Dimension	Value (μm)	Dimension	Value (μm)
La	1000	Lt1	50
wa	3	Lt2	150
Φa (degrees)	3	Lt3	15
Lc	100	wt	3
wc	3	st	10

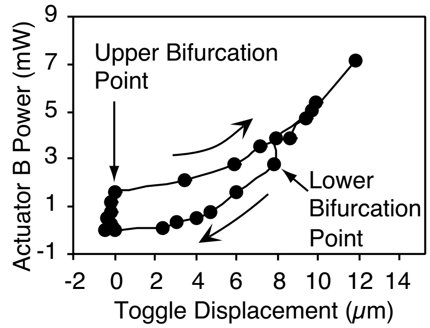

Fig. 6: Measured hysteresis in the mechanical displacement of the toggle in response to power supplied to actuator *B*.

as the electrical output signal.

Figure 7 shows individual frames from a video that captured the oscillator in operation. The initial state is observed in Fig 7(a): the switch is on, and the thermal actuator is being supplied with power. In deflected state, observed in Fig 7(b), the switch is open and not conducting current, while the toggle is in the snapped mode.

To measure the electrical signal generated by the oscillator, the setup in Fig 3 was used. The voltage across the oscillator, Vosc, was measured using the four point probe technique and the current was measured by passing it through a shunt resistor, R and measuring the voltage across it, Vcur. The output waveform obtained from the Type I oscillator as observed on an oscilloscope is shown in Fig 8. Vcur is zero when no current flows through the resistor and at a fixed value proportional to the current, while there is current flow. The square wave obtained for Vcur shows that the current through the shunt resistor is being turned on and off at regular intervals by the action of the oscillator switch. Vosc also changes as the switch opens and closes. When the switch is open, Vosc is at a high value corresponding to the supply voltage due to the infinite resistance of an open switch. The closure of the switch causes the Vosc to drop to a low value corresponding to the small resistive voltage drop across the closed switch. These observations validate the basic operation of the oscillator.

The oscillator was further characterized by varying the supply voltage and measuring the resulting frequency, duty cycle and power consumed. Figure 9 shows the oscillation

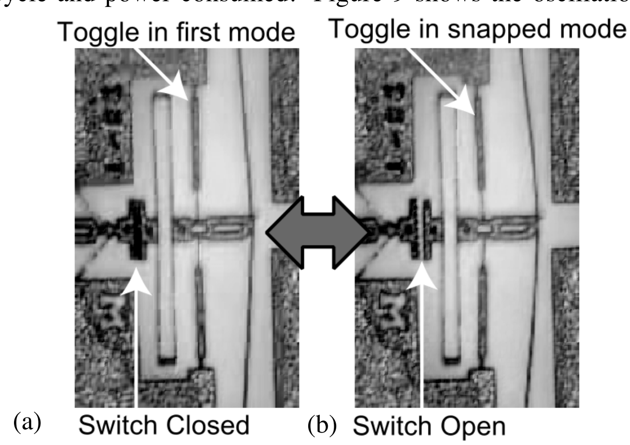

Fig. 7: Video frames capturing oscillator operation and showing the two states in the operating cycle of the oscillator. In the initial state (a, left) the switch is closed and the toggle is at rest. In the deflected state, (b, right) the switch is open and the toggle is in the deformed mode.

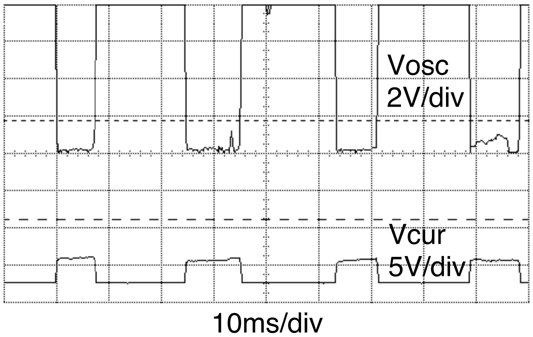

Fig. 8: Output waveform as obtained on an oscilloscope for the Type I oscillator with a supply DC voltage of 0.3 V.

frequency and duty cycle of a Type I oscillator obtained experimentally. The frequency remained relatively constant at 39 Hz, while the duty cycle changes with power supplied. The mean value of the frequency obtained was 38.46 Hz with a maximum deviation of ±6 %. The maximum current switched by the oscillator was 1.03 amp while the voltage applied across the oscillator was between 50 to 100 mV.

As indicated previously, the Type II oscillator exploits the intrinsic thermal hysteresis present in an electrothermal actuator. Due to the smaller effective hysteresis, this design generates oscillations of a higher frequency than Type I. Figure 10 shows the frequency and the duty cycle changing with the power consumed by actuator *B* for a Type II device. The frequency of this oscillator depends on the actuator power and varies between about 1000 Hz to 200 Hz, while the duty cycle changes from about 0.7 to 0.3 with increasing actuator power. A current of 0.5 amp was switched by the thermal hysteresis oscillator while requiring a voltage of 0.5 V across it.

The total power consumed by the Type II oscillator is 70-180 mW; about 95 % of which is dissipated due to the contact resistance of the switch. This power loss is 50x the power consumed by the actuator. These observations indicate that the power consumption of the oscillator could be reduced by an appreciable amount by increasing the effective resistance of the actuator.

V. CONCLUSIONS

Both types of mechanical oscillators reported in this paper can generate a modulating signal from a DC source without the use of any electrical components. The type using structural hysteresis generates a signal with relatively constant frequency of about 39 Hz at different power levels, with a variable duty cycle from 0.3 to 0.6. In contrast, the oscillator using thermal hysteresis is tunable, with a

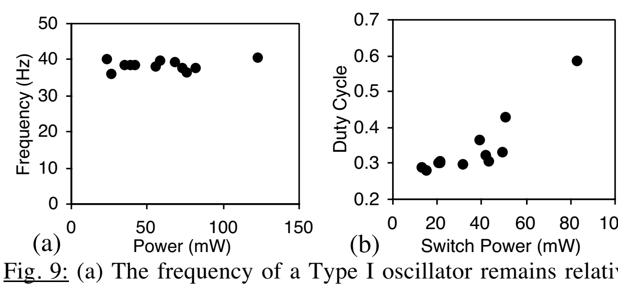

Fig. 9: (a) The frequency of a Type I oscillator remains relatively constant at 39 Hz for different power levels. (b) The duty cycle of the oscillator is a function of the contact resistance of the switch.

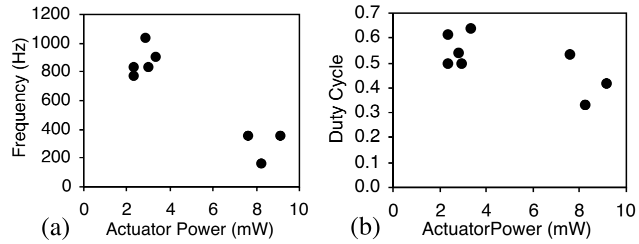

Fig. 10: (a) Type II oscillator generates a signal with a maximum frequency of 1160 Hz that depends upon the power consumed by the actuator. (b) The duty cycle also depends on actuator power.

frequency range from 200 to 1200 Hz and a duty cycle from 0.3 to 0.7. A supply voltage of less than 0.5 V is required for the oscillators, each of which has a footprint of about 1 mm x 1 mm. With the implementation if these devices we demonstrate the use of purely mechanical components to generate oscillating signals. The use of MEMS switches allows the devices to have a high power handling capacity and can be use to drive sensors and actuators as well as make on-chip voltage converters for high voltage applications.

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