A Combined MEMS Threshold Pressure Sensor and Switch

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***Abstract*—In this study, a combined threshold pressure sensor and switch is introduced. The sensor detects when the pressure drops below a threshold value and automatically triggers a switch without the need for any computational overhead to read the pressure or trigger the switch. This system exploits the significant fluid interaction of a MEMS beam undergoing a large oscillation from electrostatic levitation to detect changes in ambient pressure. The levitation electrode configuration is combined with a parallel-plate system by adding an extra voltage to an electrode that is traditionally grounded, giving the system the ability to simultaneously act as a switch by toggling to and from the pulled-in position. It is experimentally demonstrated that the pressure sensing/switching mechanism is feasible and the threshold pressure to trigger the switch can be controlled by adjusting the voltage applied to the switch electrode.**

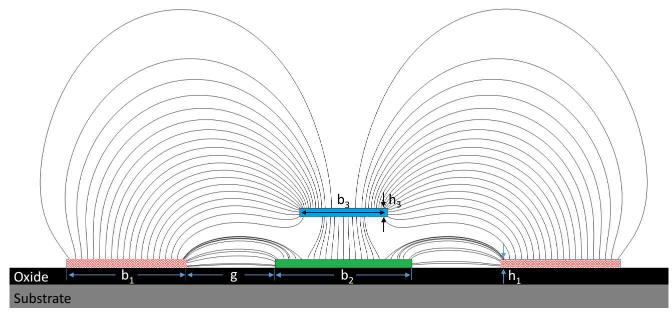

Fig. 1. Electrode layout of the threshold pressure sensor and switch with geometric parameters and electric field. The value of the geometric parameters are given in Table I.

I. Introduction

Accurately sensing ambient pressure is an incredibly important operation in the aerospace, automotive, manufacturing, and medical industries. Traditional pressure sensors measure the deflection of a diaphragm in response to an applied pressure and create an electrical signal [1]. In micro-electro-mechanical systems (MEMS), this is typically achieved using piezoelectric materials that generate a voltage when undergoing mechanical strain. These types of pressure sensors will continually give a quantitative measurement of the pressure that can be read by a computer. However, some applications only need to trigger a response when the pressure passes a certain value, such as tire pressure in a car. This requires the output of a MEMS pressure sensor to be constantly monitored and interfaced with a switch that is triggered when the pressure passes the specified value [2]. A pressure sensor that automatically triggers a response would eliminate the need for constant monitoring of the pressure and could potentially simplify the entire system while reducing the cost of the sensor.

One way this could be achieved is by using the switch proposed by the authors in [3] as a resonator. The switch utilizes an electrostatic levitation electrode configuration [4]–[7] shown in Figure 1. A cantilever is suspended above three electrodes fixed to the substrate. The side electrodes (red) are given a voltage relative to the center electrode (green) and beam (blue). The electric field from the side electrodes pulls on the top of the beam more than the bottom, producing a net force upwards. A bias voltage is placed on the center electrode to generate an attractive force that pulls the beam back down. The switch works by applying the pull-in voltage to the center electrode to initiate pull-in, creating a connection between the beam and center electrode. By applying a large voltage on the side electrodes, the beam can be released from pull-in, opening the switch. If the beam is used as a resonator, dynamic pull-in can be triggered if the beam travels too close to the center electrode.

Electrostatic levitation can produce very large oscillations that are over an order of magnitude larger than the anchor height of the beam [8], [9]. Previous experimental results showed the beam oscillating almost 25 μm peak-to-peak, with the tip repeatedly tapping on the center electrode. As reported by the authors in [9], the beam dynamics are heavily influenced by the surrounding air when the dynamic amplitude is large. The large oscillation in close proximity to the substrate creates a considerable air spring effect that significantly influences the dynamic amplitude.

The working principle of the threshold sensor is based on the strong coupling between the beam and fluid dynamics. If the oscillation reaches a sufficiently high amplitude, dynamic pull-in is triggered and the beam sticks to the center electrode. The oscillation amplitude that the beam can achieve is dependent on the air spring effect and nonlinear damping, which occur when the beam gets close to the substrate. High ambient pressure creates a large air spring effect that acts as a cushion and prevents dynamic pull-in from occurring. When

Parameter	Variable	Value
Beam Length	L	505 μm
Beam Width	b_3	20.5 μm
Beam Thickness	h_3	2 μm
Anchor Height	d	2 μm
Electrode Side Gap	g	20.75 μm
Side Electrode Width	b_1	32 μm
Center Electrode Width	b_2	28 μm
Electrode Thickness	h_1	0.5 μm

TABLE I
BEAM PARAMETERS

the pressure drops, the air spring effect decreases allowing the beam to get closer to the center electrode. If the pressure drops below a threshold value, the beam gets close enough to trigger dynamic pull-in and the switch closes.

This system does not require constant monitoring of the pressure because the switch is closed automatically in response to the decreasing pressure. Other methods require detecting changes in stiffness by measuring a shift in resonant frequency [10], which is more difficult to control than voltage. The pressure at which pull-in occurs is proportional to the bias voltage on the center electrode. Because of this, the sensor is tunable and can be set to trigger at any pressure within a certain range.

II. EXPERIMENTAL METHODS

The sensor/switch is fabricated to the dimensions in Table I using PolyMUMPs [11]. A schematic of the experimental setup is shown in Figure 2. The beams are placed in a vacuum chamber and the pressure is reduced to around 1 Torr. $1V_{AC}$ and $170V_{DC}$ are applied to the side electrodes and a constant bias voltage ranging from 6-12V is applied to the center electrode. A large DC offset on the side electrodes is used to push the beam tip up approximately 11μm. This, combined with the anchor height, gives an initial gap of 13μm at the tip. However, the bias voltage will pull the tip down about 1μm, bringing the actual gap to around 12μm. The large initial gap gives the beam room to generate a high amplitude oscillation before hitting the center electrode. The large oscillation is needed to create a strong interaction with the surrounding air. The AC frequency on the side electrodes is swept downward from 13kHz to 8kHz (across the first natural frequency). The beam tip velocity is measured with a laser vibrometer.

The amplitude at the resonant peak depends on the squeeze film damping of the system. If the pressure is below a threshold value, the peak amplitude will become large enough that dynamic pull-in is triggered and the switch closes. The bias voltage is increased incrementally until the beam experiences pull-in during the frequency sweep. The minimum voltage needed to induce pull-in at the surrounding air pressure is recorded, and this process is repeated for a number of pressures between 0.7 and 1.6 Torr.

III. RESULTS AND DISCUSSION

Figure 3 shows the time data for the test at 1.39 Torr and a bias voltage of 9.9V (a) and 10V (b). As the frequency approaches the natural frequency, the oscillation amplitude

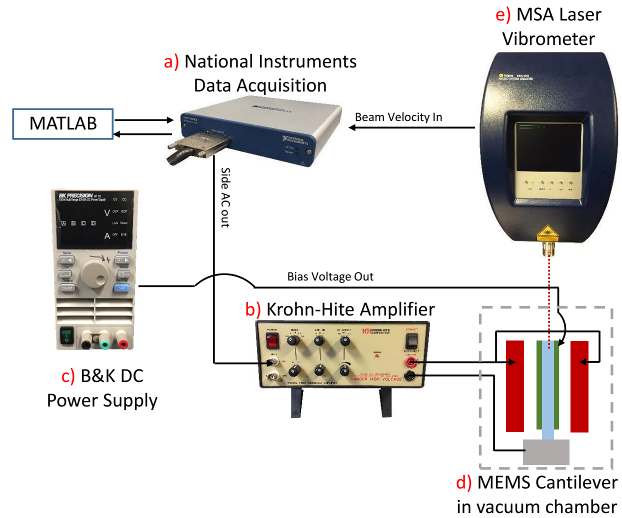

Fig. 2. Set up of the experiment with specific equipment used for the testing.

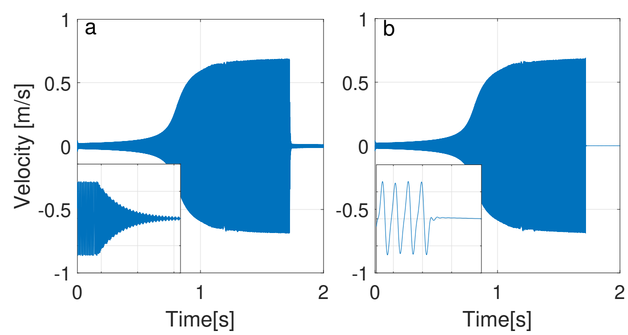

Fig. 3. Beam tip velocity vs time at 1.39 Torr and a) 9.9V_{bias} and b) 10V_{bias}. The beam does not experience pull-in at 9.9V, but does at 10V. The inlet of both figures shows how the response behaves after the natural frequency has been passed.

increases significantly. At 9.9V, when the frequency drops below the resonant frequency, the system experiences hysteresis and drops to a significantly smaller oscillation amplitude. In this case, the beam does not pull-in and maintains a stable oscillation. If the bias voltage is increased to 10V, when the driving frequency approaches the natural frequency, the beam becomes unstable and collapses to the center electrode. This can be seen in the inlet of Figures 3a and 3b, which show how the beam behaves at approximately 1.7s when the instantaneous AC frequency is about 8.7kHz. Therefore, at 1.39 Torr the bias voltage should be 10V to trigger pull-in and close the switch.

Figure 4 shows a zoomed in portion of Figure 3b, with an estimate of dynamic displacement. The dynamic displacement is calculated by integrating the velocity signal in the frequency domain. The beam experiences a peak-to-peak tip displacement of almost 22μm. If the static tip position of the beam is only approximately 10μm (plus the 2μm anchor height), that means the beam tip is oscillating at a gap from 23μm to about 1μm at a frequency of around 8.7kHz. The large change in gap is having a noticeable effect on the velocity and displacement of the beam. When the beam is at its upper extreme and the gap is large, the beam moves like a simple linear oscillator.

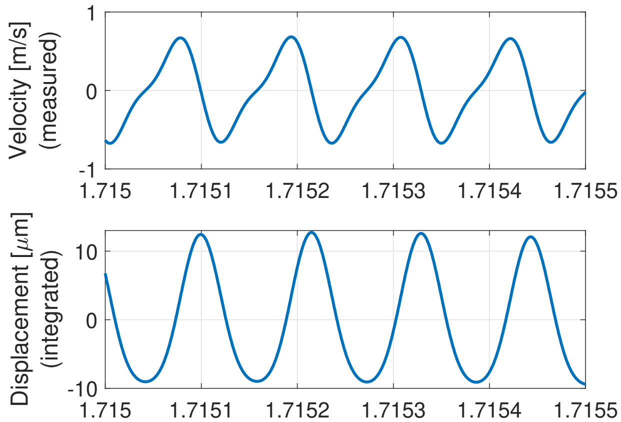

Fig. 4. Zoomed in velocity data with estimated displacement.

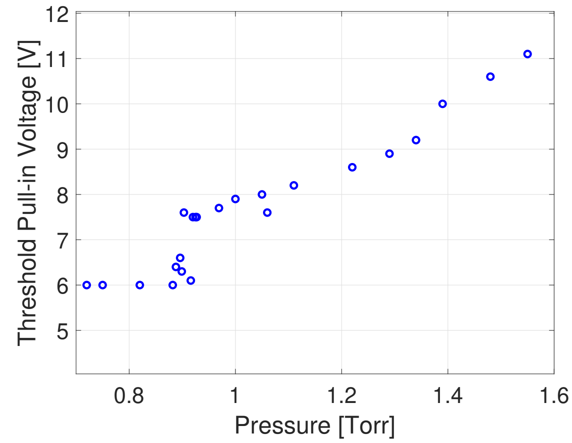

Fig. 5. Pressure vs pull-in voltage at various pressures.

However, at the lower extreme when the gap is very small, the velocity slows down and the displacement peak flattens out. This is a result of the large nonlinear damping that is much more significant when the gap is small. Because the frequency is high, there is also an air spring effect coming from the compressibility of the air. While this nonlinearity is usually undesirable in MEMS resonators, in this case it is desirable because it demonstrates that beam dynamics are heavily influenced by the ambient air pressure.

The test is repeated for many pressure levels between 0.7 and 1.6 Torr. The relationship between pressure and threshold pull-in voltage is shown in Figure 5. The results show an upward trend in pull-in voltage with increasing pressure. This proves the threshold pressure senor and switch concept is valid. Higher pressure limits the oscillation amplitude and requires a higher bias voltage to experience pull-in during the frequency sweep. For example, to trigger the switch at 1 Torr, a bias voltage of 8V should be applied to the center electrode. However, if the switch should trigger at 1.4 Torr instead, 10V would need to be applied to the center electrode.

One interesting behavior that is seen in the experiment is at 0.9 Torr. Below this pressure, the threshold pull-in voltage stays constant at around 6V. At 0.9 Torr the threshold voltage jumps up to about 7.5V before linearly increasing with pressure at a rate of around 5V/Torr. This indicates that there is some minimum pressure, below which the sensor/switch will not work. This is because if the pressure is too low, the air will not exert enough force on the beam to significantly affect its motion, even with a large oscillation. Therefore, the threshold pull-in voltage will remain relatively constant. However, this lower limit should be adjustable by changing the geometry of the sensor/switch. In this experiment, the sensing concept is demonstrated with a beam that is only 20.5μm wide. If the resonator is a plate instead of a beam, it should be much more affected by nonlinear damping and the air spring effect, and be able to work at pressures below 0.9 Torr.

Another advantage of this system is that once the switch has been triggered, the device can be reset by removing the bias voltage. It was shown in [3] that the side voltage can lift the beam out of its pulled-in position and make the system stable again. This allows the pressure sensor/switch to be reused multiple times without permanent failure. For this experiment, the same device was used for all the data points in Figure 5, which required the beam to be released over 20 times. This had no noticeable effect on the performance of the device for subsequent tests.

IV. Conclusion

In this study, a combined threshold pressure sensor and switch is introduced. The sensor exploits the significant coupling between beam and fluid dynamics that occur with large beam oscillations from electrostatic levitation. It is demonstrated that the threshold bias voltage to induce dynamic pull-in is a function of the applied pressure and can be used to control the triggering pressure of the sensor/switch. The device requires no computational overhead to read the output of the sensor or trigger the switch as the system operates entirely through mechanical and electrical phenomena that happen automatically. This design would be very useful for applications that need to trigger a response if the pressure drops below a threshold level, such as in a car tire.

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