A New Pressure Threshold Sensor Based on Nonlinear MEMS Oscillator

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ABSTRACT

Pressure sensing is one of the earliest applications of Micro-Electro-Mechanical-Systems MEMS. Changing the pressure sensing element (such as capacitive and optical) size to the microscale has created opportunities to reduce power consumption and production costs of pressure sensors while increasing their sensitivity. However, current technology struggles with reducing the complexity of using pressure sensors in applications where measuring the amount of pressure is not as important as a threshold value for an action to occur. Examples of this complexity are the extra circuitry, controllers, and/or decision units that are needed to trigger an alarm in a car for low air-pressure in the tire, or to trip an HVAC compressor if the refrigerant pressure is lower than a threshold value. In this work, we propose a novel tunable smart threshold MEMS pressure sensor for such applications. The activation of subharmonic resonance (twice-natural frequency) for cantilever-based MEMS due to AC and DC electrostatic excitation is used to trigger the sensor at a specific threshold pressure value. This sensor can be easily tuned to trigger at different threshold pressure values by simply adjusting the AC or DC voltage values.

Keywords: Pressure, MEMS, Squeeze-Film-Damping, Subharmonic resonance, Threshold sensor

1 INTRODUCTION

Micro-electro-mechanical-systems (MEMS) are extensively studied because of their exceptional characteristics, such as, small size, low weight, high sensitivity, low response time, low signal-to-noise ratio and the ability to be cheaply manufactured and mass-produced. Those characteristics are ideal for many types of sensors and actuators. MEMS sensors have already found their ways to the market as complete products, such as accelerometers and pressure sensors [1].

MEMS pressure sensors were one of the earliest MEMS-technology applications to reach market shelves. The earliest MEMS pressure sensors utilized a diaphragm shaped microstructure (Bogue, 2007) [1] to measure the absolute pressure by measuring the change in its internal capacitance [2] or resistance [3, 4]. Nowadays, extensive research is done about MEMS diaphragm sensors to enhance their resolution and increase their sensitivity. Moreover, different pressure sensing technologies have been investigated over the years, including optical MEMS sensors [5] and [6]. In this type of MEMS design, a moving diaphragm is used as well. However, unlike typical diaphragm sensors, optical sensors measure the change in the refraction index as an indication due to the displacement of the diaphragm and relates this change to pressure variation. Furthermore, MEMS resonators were also proposed as pressure sensors. Pressure is sensed by measuring the change in MEMS resonant frequencies or by measuring the time required for the MEMS structure to collapse (pull-in) [7].

In many applications, turning a process on or off upon reaching some pressure threshold is more desirable than measuring the actual amount of pressure. For instance, cut-off pressure sensors are utilized in HVAC systems. However, current cut-off systems are expensive, which limits their use. In these applications, a simple binary pressure sensor is desired. In this paper, we propose the use of the onset of nonlinear dynamics activation of an electrically actuated micorbeam as a tunable threshold pressure sensor. The organization of this paper is as follows. In section 2, we present the model that is used to simulate the new sensor dynamic response. In section 3, we present numerical simulations, using the model developed in section 2, to validate the new sensor concept. Finally, in section 4, we conclude this paper and offer some discussion.

2 MATHEMATICAL MODEL

We model our MEMS microbeam as a single-degree-of-freedom Spring-Mass-Damper system as shown in figure (1). The system is electrostatically actuated by a DC voltage signal superimposed with AC signal.

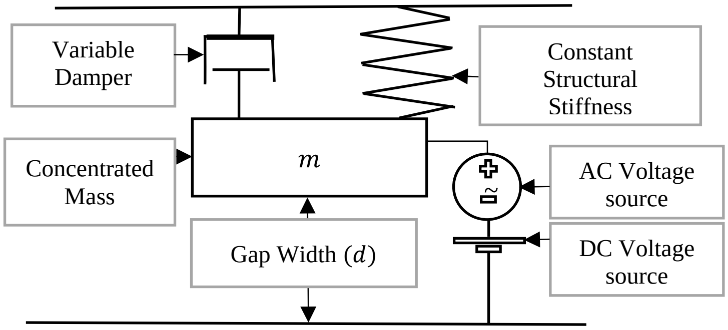


Figure 1: MEMS single degree of freedom model

In this model, the MEMS's mass is concentrated in a point. This mass can only move in a single direction. The structure's stiffness can be found experimentally or theoretically based on the support type of MEMS such as clamped-clamped or cantilever support. The equation of motion of the system is given by:

$$m_{eff}\ddot{x}(t) + c(x)\dot{x} + kx = F_e(x,t) \ldots (1)$$

Where x is the MEMS deflection, the dot operators represent temporal derivatives, (t) is the time in seconds, m_{eff} (kg) is the effective mass given by $m_{eff} = \frac{k}{\omega_n^2}$, ω_n is the natural frequency of the system (rad/s), k is the linear stiffness of the microbeam (N/m), $c(x)$ is the nonlinear squeeze film damping of the system given by equations (2)-(6) [8,9]:

$$\lambda = \frac{\lambda_0 P_0}{P_a} \ldots (2)$$

$$Kn = \frac{\lambda}{d} \ldots (3)$$

$$\mu_{eff} = \frac{\mu}{1 + 9.638Kn^{1.159}} \ldots (4)$$

$$\sigma(x) = \frac{12A\Omega\mu_{eff}}{P_a(d-x)^2} \ldots (5)$$

$$c(x) = \frac{64\sigma(x)P_a A}{\pi^6\Omega(d-x)} \frac{1+\beta^2}{\left[(1+\beta^2)^2 + \frac{\sigma^2}{\pi^4}\right]} \ldots (6)$$

Where P_a is the ambient (operation) pressure, λ, λ_0 are the mean-free path of gass molecules at the operation pressure and atmospheric pressure (P_0), respectively, Kn is the Knudsen number, d is the nominal gap width of the MEMS, μ is the nominal dynamic viscosity constant of air $(N.s/m)$ and μ_{eff} is the effective viscosity constant of air to account for slip flow $(N.s/m)$, $\beta = \frac{b}{l}$ is the shape ratio which equals the ratio between the width of the microbeam b and length l, Ω is the excitation AC frequency, $A = bl$ is the area of overlap between the microbeam and the substrate underneath it, and $\sigma(x)$ is the squeeze number.

Equations (5) and (6) show that the system's damping is a function of pressure. Therefore, pressure is expected to change the resonance frequencies of the system as follows:

$$\omega_r = \omega_n\sqrt{1-\zeta^2} \ldots (7)$$

Where ω_r is the resonance frequency of the MEMS and ζ is the system damping ratio. The MEMS is actuated electrostatically using a combination of AC and DV voltages to produce the electrostatic force F_e :

$$F_e = \frac{\epsilon A[V_{DC} + V_{AC}Cos(\Omega t)]^2}{2(d-x)^2} \ldots (8)$$

where, V_{DC} and V_{AC} are the DC and AC voltage, respectively (V), ϵ is the permittivity of air (F/m).

The MEMS model is highly nonlinear due to electrostatic actuation and the squeeze film damping effect, which as shown before depends greatly on pressure. These nonlinearities activate subharmonic resonance, twice the natural frequency, at certain pressure and voltage values. The subharmonic activation is characterized by a sudden jump-discontinuity in the MEMS deflection-amplitude [10]. Subharmonic resonance requires low damping (pressure) and high input voltage to be activated. Thus, at a given high AC voltage, there is always a pressure threshold value below which only the subharmonic resonance is active.

3 RESULTS AND DISCUSSION

In this work, a Sensata™ MEMS sensor is used with following dimensions: $l = 900\mu m$, $b = 532\mu m$, $k = 215\ N/m$, $\omega_n = 192.5\ Hz$, $d = 42\mu m$ [10]. Figure 2 shows simulation for the MEMS response under slightly different ambient pressure values and the same electrostatic force ($V_{DC} =\ 30V$ and $V_{AC} = 64\ V$). Under low ambient pressure of $P = 70\ Pa$ the subharmonic response is observed. This response is characterized by a sudden, large amplitude jump. Furthermore, the MEMS vibrates at half the excitation frequency. At some cut-off pressure ($P = 88\ Pa$ in the figure), the subharmonic resonance behavior dies-out and the MEMS vibration amplitude is very low and has the same frequency as the actuation AC voltage. This strong subharmonic resonance dependency on pressure motivates the idea of our new threshold pressure sensor.

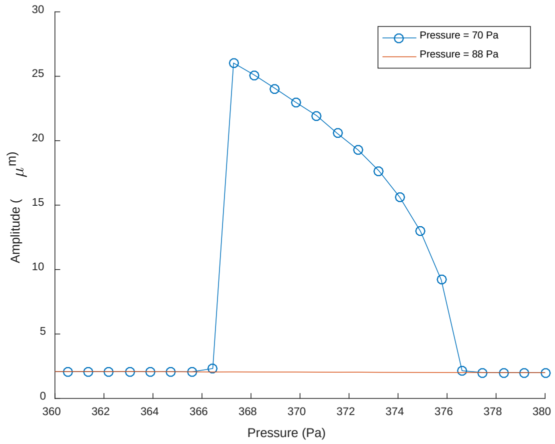
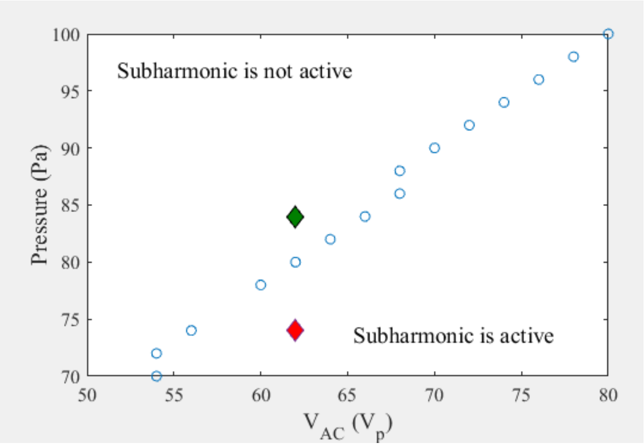
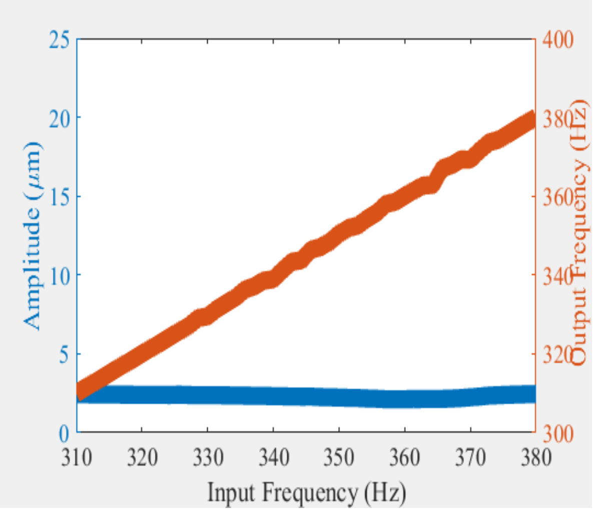


Figure 2: Response of the MEMS around subharmonic frequency range. The MEMS exhibits a subharmonic response at $70\ Pa$*. This response seizes to exist at* $88\ Pa$*.*

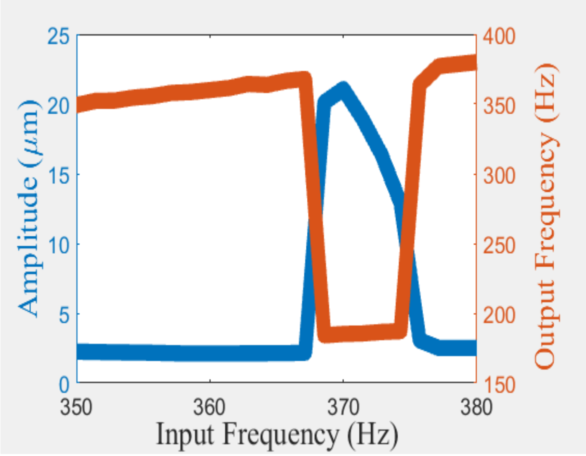
The basic idea of the new pressure threshold sensor can be understood by observing Figure 3.a where the activation of subharmonics resonance is plotted against pressure. One can tune to the desired pressure threshold for sensor activation by adjusting the AC voltage, for example, at *80 Pa* by supplying $V_{AC}=62\ V$ as shown in the figure. If pressure is above *80 Pa*, then subharmonic resonance is not activated. This can be observed by the low MEMS deflection in Figure 3.b. If the pressure is below the threshold value of *80 Pa*, subharmonic resonance is activated and a sudden jump in the MEMS deflection is observed. Moreover, the MEMS output frequency dropped to almost half of the excitation frequency. This sudden change in the output frequency as mentioned before can also be used to detect the subharmonics activation. These activation signals can be applied directly to useful functionality without adding complexity to the system.



(a)



(b)



(c)

Figure 3. (a) Subharmonic activation diagram as a function of pressure and AC voltage, (b) an inactive subharmonic resonance($P > P_{cut\ off}$)*, and (c) an active subharmonic resonance* ($P < P_{cut\ off}$)*.*

4 CONCLUSION

In this paper, we presented a novel concept for a digital pressure sensor by taking advantage of the nonlinear, digital-like, subharmonic resonance activation in MEMS. We showed that once the subharmonics resonance is activated, the MEMS exhibits large vibrations at twice the actuation frequency. This occurs if the ambient pressure is below a cut-off threshold value. Once the ambient pressure is above threshold value, the MEMS vibrations are small with a frequency equal to the excitation frequency. Finally, we showed that the new pressure sensor could be easily tuned to trigger at different threshold pressure values by simply adjusting the AC or DC voltage values.

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