A new humidity sensor based on the effect of water content on a capacitive MEMS oscillator's thermal characteristics

M. H Hasan* and F. Alsaleem**

*University of Nebraska - Lincoln, NE, USA, mohammadhhasan@huskers.unl.edu
**University of Nebraska - Lincoln, NE, USA, falsaleem2@unl.edu

ABSTRACT

Accurate humidity measurement is essential in commercial and industrial applications such as HVAC systems and microelectronics manufacturing. Typical humidity sensors suffer from degradation over time, consume a relatively high amount of power, and have limited range. To overcome these problems, we present simulation for the use of uncoated capacitive MEMS oscillators to measure humidity. This new sensor concept takes advantage of the MEMS oscillator's thermo-electrical variations as the water content (humidity) of air changes. This paper shows that water changes the effect of the oscillator's squeeze-film-air damping. This results in an overall shift in its primary resonance frequency and its subharmonic resonance frequency (twice the resonance frequency). The results of an extensive simulation for a capacitive MEMS oscillator, lumped in a spring-mass-damper model, will be used to calibrate the oscillator amplitude and frequency changes to humidity.

Keywords: Humidity, MEMS, Squeeze-Film-Damping, Subharmonic sensor, non-coated

1 INTRODUCTION

Resistive- and capacitive-based sensing technologies were proposed to measure humidity. Capacitive sensing, the most common [1], relies on the change of the dielectric constant of the sensor due to the changes of air properties, absorption of moisture into the sensing element, a chemical reaction between the sensing element and the moisture, or a combination of the three. Due to their mass production and low power requirement, MEMS devices are becoming more popular for sensing humidity. Static [1,2] and dynamic excitation [3] are the most common operating modes for MEMS humidity sensors and other sensing approaches, such as mass and gas sensing [4]. MEMS humidity sensors are typically coated by polymer or ceramic materials. Those ceramics usually have limited life [5-8] or a have a low sensing range [7]. In this work, we demonstrate the use of an uncoated MEMS resonator to measure humidity. The changes in thermo-electrical air properties due to humidity variation will be tracked and correlated to humidity. A few studies have shown that MEMS resonator characteristics could change as the thermal conditions of air varies [9-11]. However, those effects were seen as disturbances. In this study, we show that these thermal condition effects on a MEMS resonator could be, alone, used as humidity measurement signals. Thus, increasing the expected lifespan of humidity sensors by eliminating the need for the coating layer. Subharmonic resonance, described in the next section, will be used to amplify the sensor's signal to compensate for the expected low output signal.

The organization of this paper is as follows: In section 2, we present the mathematical model for this system. In section 3, we show simulation results and discussion. Finally, we conclude with conclusion and ongoing work in section 4.

2 MATHEMATICAL MODEL

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

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

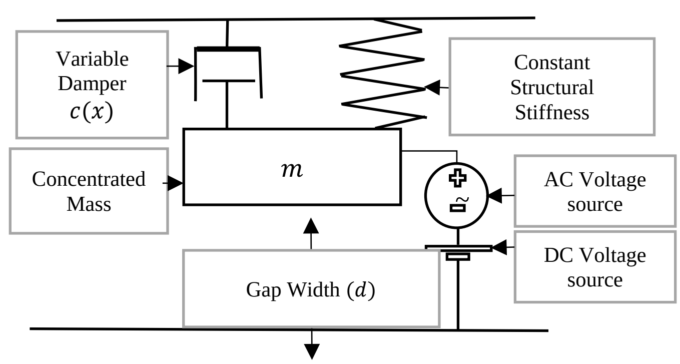


Figure 1. MEMS single degree of freedom model

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) [12,13]:

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

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

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

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

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

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.

Temperature and humidity are affecting the drag force $(\hat{F}_d)$ through changes in μ, therefore, μ_{eff}. These effects are described by [14]:

$$\mu_m = \frac{\mu_a(1-X)}{[(1-X) + X * \Phi_{av}]} + \frac{[X * \mu_v]}{[(X) + (1 + X * \Phi_{va})]} \ldots (7)$$

where μ_m is the dynamic viscosity of humid air at a given temperature, X is the absolute humidity of vapor in air, Φ_{av} and Φ_{va} are interaction parameters between dry air and water vapor and can be calculated as:

$$\Phi_{av} = \frac{\sqrt{2}}{4}\left(1 + \frac{M_a}{M_v}\right)^{-0.5}\left[1 + \left(\frac{\mu_a}{\mu_v}\right)^{0.5}\left(\frac{M_v}{M_a}\right)^{0.25}\right]^2 \ldots (8)$$

$$\Phi_{va} = \frac{\sqrt{2}}{4}\left(1 + \frac{M_v}{M_a}\right)^{-0.5}\left[1 + \left(\frac{\mu_v}{\mu_a}\right)^{0.5}\left(\frac{M_a}{M_v}\right)^{0.25}\right]^2 \ldots (9)$$

where M_a and M_v are the molar mass of dry air and water vapor (kg/mol), respectively, μ_a is the viscosity constant of dry air and μ_v is the viscosity of water vapor and are given by:

$$\mu_a = MA_0 + MA_1(\Theta_a + 273) + MA_2(\Theta_a + 273)^2 + MA_3(\Theta_a + 273)^3 + MA_4(\Theta_a + 273)^4 \ldots (10)$$

$$\mu_v = (MV_0 + MV_1 \Theta_a) \ldots (11)$$

where MA_i and MV_i are interpolating constants and Θ_a is the ambient temperature. Finally, F_e is the electrostatic force due to AC and DC voltage and is given by:

$$F_e = \frac{\epsilon A [V_{DC} + V_{AC} Cos(\Omega t)]^2}{2(d-x)^2} \ldots (13)$$

where V_{DC} and V_{AC} are the DC and AC voltage, respectively (V) and ϵ is the permittivity of air (F/m). Given the nonlinear forcing function, one can represent equation (1) using Duffing equation. Therefore, the system retains a unique characteristic of an amplified response at half and twice its natural frequency. Those frequencies are called Superharmonic and Subharmonic resonance frequencies, respectively. In this paper, subharmonic resonance is the frequency of interest. A shift in the subharmonic frequency, due to changes in damping, is used as an indication to changes in air temperature and absolute humidity.

3 RESULTS AND DISCUSSION

In this work, a Sensata™ MEMS sensor is used. The dimensions used are extracted in [15]. From the aforementioned reference, $l = 900\mu m$, $b = 532\mu m$, $k = 215\ N/m$, $\omega_n = 192.5\ Hz$, and $d = 42\mu m$. Due to the size of the used MEMS sensor, it is not possible to achieve an oscillatory response at high pressure; therefore, the simulation is carried out at reduced pressure. Fig.2 shows the response of the microbeam when actuated around its subharmonic resonance frequency at $t = 25°C$, $P = 150\ Pa$, $V_{DC} = 50\ V$ and $V_{AC} = 50\ V\ (RMS)$. The absolute humidity of the vacuum chamber are assumed to vary between 0% and 40%.

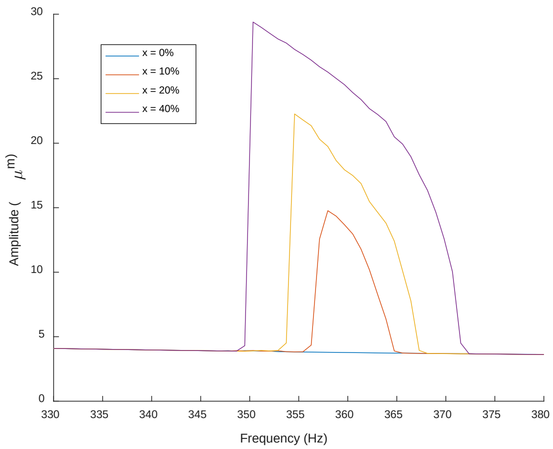


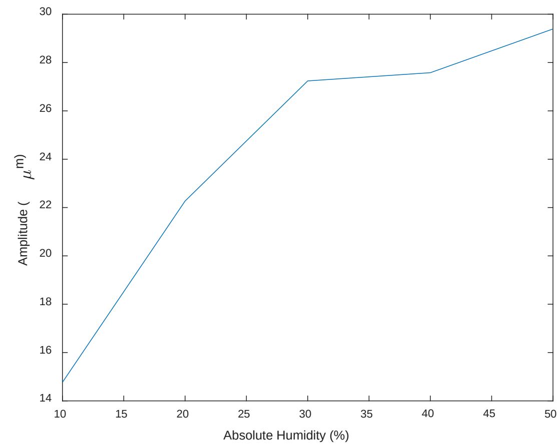
Figure 2. Frequency response of the proposed MEMS sensor around its subharmonic resonance frequency, $t = 25°C, P = 150\ Pa, V_{DC} = 50\ V\ and\ V_{AC} = 50\ V\ (RMS)$.

Subharmonic resonance response has a distinct behavior characterized by a big and sudden amplitude jump at the subharmonic frequency (around twice the natural frequency). To achieve such response, the system must be appropriately underdamped. Fig.2 shows that the subharmonic resonance response seizes to exist for absolute humidity $x = 0$. Increasing the absolute humidity, and thus the water content in air, reduces the system's damping, allowing subharmonic resonance response to be activated. In addition, Fig.2 shows that the subharmonic resonance frequency (which is the frequency at which the jump occurs) decreases as water content increases. This is accompanied by a significant increase in the amplitude of the vibration.

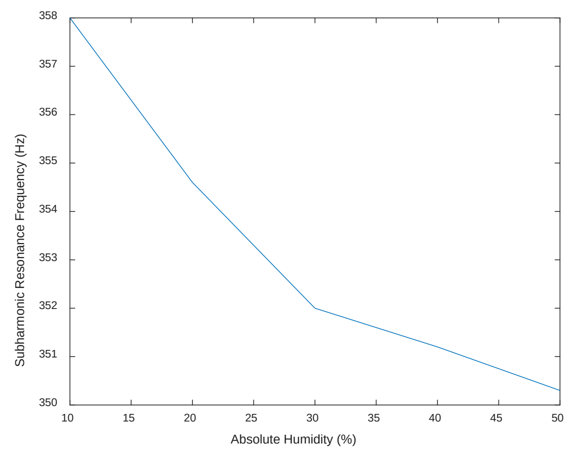
Fig. 3 illustrates the effects of moisture content on the subharmonic resonance frequency and the maximum oscillation amplitude. Fig. 3(a) shows a significant increase in the amplitude of vibration as the moisture content increases. On the other hand, subharmonic resonance frequency appears to decrease as the absolute humidity increases. Thus, it is possible to use either of those two parameters to indicate the amount of moisture content in air.

4 CONCLUSION

In this work, we showed the concept of a novel absolute humidity sensor. Our proposed sensor utilizes the nonlinear amplification response of MEMS through subharmonic frequency (twice the natural frequency). Thus enabling a MEMS device running in air to provide very high sensitivity to humidity, low power consumption and long life. Those features combined are not typical in a standard humidity sensor.



(a)



(b)

Figure 3. Relationship between: (a): Absolute humidity and the maximum oscillation amplitude, (b) Absolute humidity and the subharmonic resonance frequency.

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