2018

Simultaneous electrical and mechanical resonance drive for large signal amplification of micro resonators

M. H. Hasan  
*University of Nebraska-Lincoln*, mohammadhhasan@huskers.unl.edu

F. M. Alsaleem  
*University of Nebraska-Lincoln*, falsaleem2@unl.edu

N. Jaber  
*King Abdullah University of Science and Technology*

M. A. A. Hafiz  
*King Abdullah University of Science and Technology*

M. I. Younis  
*King Abdullah University of Science and Technology*, Mohammad.Younis@kaust.edu.sa

Follow this and additional works at: [https://digitalcommons.unl.edu/archengfacpub](https://digitalcommons.unl.edu/archengfacpub)

Part of the [Architectural Engineering Commons](https://digitalcommons.unl.edu/archengfacpub), [Construction Engineering Commons](https://digitalcommons.unl.edu/archengfacpub), [Environmental Design Commons](https://digitalcommons.unl.edu/archengfacpub), and the [Other Engineering Commons](https://digitalcommons.unl.edu/archengfacpub)

Hasan, M. H.; Alsaleem, F. M.; Jaber, N.; Hafiz, M. A. A.; and Younis, M. I., "Simultaneous electrical and mechanical resonance drive for large signal amplification of micro resonators" (2018). *Architectural Engineering -- Faculty Publications*. 110. [https://digitalcommons.unl.edu/archengfacpub/110](https://digitalcommons.unl.edu/archengfacpub/110)

This Article is brought to you for free and open access by the Architectural Engineering at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Architectural Engineering -- Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
Simultaneous electrical and mechanical resonance drive for large signal amplification of micro resonators

M. H. Hasan,1 F. M. Alsaleem,1 N. Jaber,2 M. A. A. Hafiz,2 and M. I. Younis2,a

1Durham School of Architectural Engineering and Construction, University of Nebraska Lincoln, Lincoln, Nebraska 68182-0816, USA
2Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

(Received 5 December 2017; accepted 4 January 2018; published online 12 January 2018)

Achieving large signal-noise ratio using low levels of excitation signal is key requirement for practical applications of micro and nano electromechanical resonators. In this work, we introduce the double electromechanical resonance drive concept to achieve an order-of-magnitude dynamic signal amplification in micro resonators. The concept relies on simultaneously activating the micro-resonator mechanical and electrical resonance frequencies. We report an input voltage amplification up to 15 times for a micro-resonator when its electrical resonance is tuned to match the mechanical resonance that leads to dynamic signal amplification in air (Quality factor enhancement). Furthermore, using a multi-frequency excitation technique, input voltage and vibrational amplification of up to 30 times were shown for the same micro-resonator while relaxing the need to match its mechanical and electrical resonances. © 2018 Author(s).

All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5018321

Micro/nano-electromechanical system (M/NEMS) devices have been used in many applications, such as high-frequency switches,1 sensors,2–9 micro-mirrors,10 and RF amplifiers.11 However, due to their high input voltage requirement, MEMS devices are still not employed to their potential.12 To amplify the output signal of MEMS resonant devices several approaches have been utilized, including driving them around their mechanical resonance frequency, optimizing designs13–15 by increasing the MEMS structure surface area, reducing its stiffness, or narrowing the gap between the stationary and movable electrodes. However, these methods were not effective to boost the device response while reducing their operating voltage to a level compatible with complementary metal-oxide semiconductor (CMOS) technology. Moreover, most of these methods increase squeeze film damping16 and the risk of electrode stiction.17 Other research have focused on utilizing parametric nonlinear resonance to increase MEMS dynamic deflection and enhance the output voltage.18–20 However, parametric resonance activation requires complex actuation techniques to modulate the stiffness and strict low damping conditions; and hence is limited for specific applications.

In this work, we report the amplification of the response of a MEMS resonator at resonance by simultaneously activating its electrical and mechanical resonances (double resonance actuation). Moreover, a multi-frequency signal21–23 was utilized to trigger the double resonance in MEMS resonators with a mechanical and electrical natural frequency mismatch.

Toward this, we fabricated a clamped-clamped microbeam resonator, as shown in Fig. 1(a). The microbeam is fabricated on a silicon wafer coated with 500 nm of thermally grown silicon dioxide (SiO2) layer. The lower electrode is formed by pattering the Cr/Au layer that is sputtered on the wafer surface. The microbeam is composed of a 4.2 µm polyimide layer coated from top with 50/200 nm Cr/Au layer. This layer is used to define the beam dimensions and act as hard mask to

Corresponding author. Electronic mail: Mohammad.Younis@kaust.edu.sa
FIG. 1. (a) A schematic of the clamped-clamped microbeam resonator, and a table showing different materials used for fabrication and their properties. (b) Electrical equivalent circuit representation of the MEMS resonator showing the motional components \( R_m, C_m \) and \( L_m \) and the nominal capacitance, \( C_e \). (c) The measurement circuit showing the MEMS resonator, a voltage source (DAQ), external inductor, parasitic resistor, and measurement devices (Laser Doppler Vibrometer for the measurement of the mechanical response, and a digital multi-meter to record the voltage across the MEMS capacitor \( C_e \) for the electrical characterization).

Protect the beam during the reactive ion etching (RIE). The upper electrode is formed by coating the beam from bottom with 50/200/50nm of Cr/Au/Cr. The Cr is used to enhance the adhesion of the polyimide layer with other materials. The two electrodes are separated by 3.3 \( \mu \)m amorphous silicon layer. This layer is etched at the final stage of the fabrication to define the air gap.

We characterized the mechanical and electrical properties of the MEMS resonator by studying the frequency response near the mechanical and electrical resonances. The mechanical resonance frequency of the fundamental mode was measured to be around 123 kHz using white noise signal excitation. The MEMS device is electrically modeled as a nominal capacitance \( C_e \), formed by the deformable MEMS microbeam and the substrate beneath it, connected in parallel to a series branch of motional resistance, motional capacitance, and motional inductance, donated by \( R_m, C_m \) and \( L_m \), respectively, Fig. 1(b). We create a resonant \( R_e \) \( L_e \) \( C_e \) circuit drive by connecting the MEMS device to a variable external inductance \( L_e \), Fig. 1(c). The circuit’s external resistance \( R_e \) is the equivalent parasitic resistance from the wires and the internal resistance of the inductor \( L_e \). In our experiments, we varied \( L_e \) to control the series \( R_e L_e C_e \) resonance frequency and the voltage gain across the MEMS capacitor \( C_e \). The frequency sweep for electrical resonance characterization was conducted at ambient
pressure and the input voltage was kept low so that the effect of $C_m$, $R_m$ and $L_m$ can be minimized during this characterization step.

The frequency response for characterizing the pure electrical resonance is conducted by an impedance analyzer, as shown in Fig. 2. We identified electrical resonance by one of the two methods: (i) by monitoring the amplitude of the circuit conductance $G$ with respect to the frequency, Fig. 2(a), where the corresponding frequency at the peak conductance value represents the electrical resonance, and (ii) by monitoring the voltage across the MEMS capacitor $C_e$, where the maximum voltage is achieved at the electrical resonance frequency as shown in Fig. 2(b). The increase in the conductance is due to the circuit reactance $X_e$ going to zero at resonance, as shown in (1) and (2):

$$X_e = \frac{2\pi f L_e}{1/(2\pi f C_e)}$$  (1)

$$G = \frac{R_e}{(R_e^2 + X_e^2)}$$  (2)

where $f$ is the excitation frequency. By solving the external $R_e L_e C_e$ resonance circuit characteristic equation (3), the steady state voltage across the MEMS capacitor $C_e$ can be obtained using equation (4):

$$L_e \frac{d^2 Q}{dt^2} + R_e \frac{dQ}{dt} + \frac{1}{C_e} Q = V_{in}(t)$$  (3)

$$\frac{|V_C|}{|V_{in}|} = \frac{1}{\sqrt{(2\pi f R_e C_e)^2 + ((2\pi f)^2 L_e C_e - 1)^2}}$$  (4)

where $Q$ is the charge stored in the MEMS capacitor $C_e$, $V_{in}$ is the input voltage and $|V_C|$ is the amplitude of the voltage across the MEMS device. The electrostatic force in the MEMS resonator is a function of the square of the voltage across the movable and stationary electrodes, and is given by:

$$F_e = \varepsilon b V_e^2 / [2(d - w(x, t))]^2$$  (5)

where $F_e$ is the electrostatic force per unit length, $\varepsilon$ is the air permittivity, $d$ is the gap between the microbeam and the substrate beneath, $x$ is the location along the length of the microbeam, $t$ is time and $w(x, t)$ is the out-of-plane deflection of the microbeam in the direction of the substrate.

Next, we compare the response of the MEMS device with simultaneous activation of electrical and mechanical resonances to that actuated using conventional mechanical resonance alone. Fig. 3(a) shows the response of the device operated at atmospheric pressure, with $V_{DC} = 30V$, and for various AC voltages. We note that for this experiment we have disconnected $L_e$. Fig. 3(b) shows the response of the double resonance driven circuit at the same pressure but with $V_{DC} = 10V$. In order

![Fig. 2. (a) Variation of electrical resonance frequency with respect to inductance. For higher inductance values the total resistance value increases, hence, a drop in the conductance value is expected. (b) The frequency response of the voltage across the MEMS device (with $L_e = 0.5mH$) that shows voltage amplification at the frequency where the conductance is shown to be maximum in (a) for two different small input voltages of 300mV and 400mV.](image)
FIG. 3. The frequency response of the MEMS resonator at atmospheric pressure driven by: (a) mechanical resonance alone for $V_{DC} = 30$V (no external inductance). (b) Double resonance drive with $V_{DC} = 10$V and $L_e = 4$ mH (electrical resonance = 116 kHz).

to activate double resonance, the electrical resonance frequency was tuned to be near the mechanical resonance frequency by using $L_e = 4$ mH. To compare the two actuation methods, we find the product $V_{AC}V_{DC}$ that results in similar maximum vibrational amplitudes. For instance, to achieve a response of 0.7 $\mu$m, the required product of $V_{AC}V_{DC}$ without electrical resonance is 750 V$^2$ compared to only 50 V$^2$ when both resonances are simultaneously activated. Thus, as the DC component of the signal remains unamplified, we show an effective 15 times voltage amplification of the AC actuation signal by driving the MEMS resonator with double resonance drive. We note that the system resonance frequency is slightly less in Fig. 3 for the case of the double resonance drive compared to mechanical resonance alone. This softening behavior is an indication of the strong nonlinearities due to the electrical and mechanical resonance coupling similar to those achieved by high voltage excitation. However, when a double resonance MEMS is used as a sensor, the MEMS electrical resonance frequency is almost fixed and any change in the overall system resonance frequency is due to the effect of the measured entity on the mechanical resonance frequency.

While double resonance activation was simple to achieve for the experimental results shown in Fig. 3(b), due to the proximity of the systems’ mechanical and electrical resonance frequencies, this might not be the case for general MEMS devices. To overcome this limitation, we introduce a multi-frequency excitation signal composed of a beating signal with two frequency components: $f_1$ and $f_2$. Due to the quadratic voltage term shown in Equ. (5), the frequency spectrum of the resulting electrostatic force include 23 $2f_1, 2f_2, (f_1+f_2),$ and $(f_1-f_2)$ frequency components. Therefore, for double resonance activation, either $f_1$ or $f_2$ is selected to be around the electrical resonance frequency while at least one of the forcing spectral components is made to be equal to the mechanical resonance frequency. To demonstrate this concept, we show in Fig. 4, the response of the MEMS resonator to a multi-frequency input signal with electrical resonance frequency at 308 kHz and a mechanical resonance frequency at 123 kHz (a mismatch of 185 kHz). We note that this experiment was also conducted under atmospheric pressure. In Fig. 4(a), the input signal has a fixed frequency component, $f_1 = 308$ kHz at different $V_{AC1}$ values, near the electrical resonance frequency, while the second frequency component $f_2$, was swept such that $(f_1-f_2)$ is near the mechanical resonance (123 kHz). This resulted in voltage amplification of $V_{AC1}$ across the MEMS resonator (capacitor) due to the electrical resonance and overall forcing amplification, hence, higher amplitude of motion. In contrast, when both $f_1$ and $f_2$ are far from the electrical resonance frequency, significantly higher input voltages are required to achieve comparable results, as shown in Fig. 4(b). For instance, to achieve an amplitude of 0.36 $\mu$m, the product of $V_{AC1}V_{AC2}$ is 1176 V$^2$ while the required $V_{AC1}V_{AC2}$ with double resonance drive is about 39 V$^2$. Thus, Fig. 4(b) demonstrates a voltage amplification gain of ~30 through double resonance excitation. This amplification is almost twice the amplification obtained in Fig. 3(b) by matching the resonator electrical resonance to its mechanical resonance using a larger inductor. We attribute this higher gain to the flexibility of using a smaller external inductor, and hence less parasitic resistance, when matching the two frequencies is not required. Finally, to demonstrate the increase in the quality factor of the system, we compare the response of the MEMS device with and
FIG. 4. The frequency response of the MEMS device for: (a) Mixed frequency excitation away from the electrical resonance frequency: $f_1$ is chosen far away from the electrical and mechanical resonance frequency (80 kHz) with $V_{AC2} = 42$ V while $f_2$ was swept such that $f_1 + f_2$ is around the mechanical resonance frequency. We show that to achieve similar deflection in (a), significantly more voltage is required. (b) Double resonance excitation: $f_1$ is fixed at the electrical resonance (308 kHz) with multiple values of $V_{AC1}$, $V_{AC2} = 6.5$ V and $f_2$ is swept such that $|f_1 - f_2|$ is around the mechanical resonance. We show that to achieve similar deflection in (a), significantly more voltage is required. (c) Double resonance (blue circle, $V_{AC1} = 3$ V, $V_{AC2} = 6.5$ V, $f_1 = 308$ kHz, $f_2 = 170$ to 210 kHz, $f_{\text{effective}} = f_1 - f_2$) versus traditional mechanical resonance (red triangle, $V_{AC1} = 3$ V, $V_{AC2} = 7$ V, $f_1 = 80$ kHz, $f_2 = 20$ to 60 kHz, $f_{\text{effective}} = f_1 + f_2$). Here, $f_{\text{effective}}$ is a frequency near the MEMS mechanical resonance frequency. The figure shows the increase in the resonator quality factor using double resonance.

In conclusion, we introduced a mean of signal amplification in electrostatic MEMS resonators by utilizing electrical resonance. We demonstrated two different schemes to utilize this signal amplification to improve the dynamic response of MEMS resonators. The approach was demonstrated first by tuning the electrical resonance frequency to coincide with the mechanical resonance frequency, using a variable external inductor, which is viable when the two resonances are proximate. We have also shown a more generic approach to activate electrical and mechanical resonances simultaneously by actuating the device using a multi-frequency signal. In this case, one of the signal’s frequency components was near the electrical resonance. The other component was chosen such that at least one of the forcing spectral components (such as $f_1 + f_2$ or $f_1 - f_2$) matches the MEMS mechanical resonance. In both the cases, a high amplitude response was recorded. An increase in the quality factor of the resonator response was also shown. We note that the activation of simultaneous electrical and mechanical resonances does not require any changes in the design of MEMS devices. However, the electrical resonance frequency and its corresponding voltage gain may differ between similar devices due to parasitic capacitance and resistance variation. More precise fabrication and tuning of external electrical components (inductor, capacitor) can be used to alleviate this issue. Nonetheless, the simultaneous electrical and mechanical resonance activation scheme may alleviate the need for CMOS incompatible high AC voltage source or amplifiers for
actuating MEMS resonators, especially when operating them at moderate to atmospheric pressure is required.

This research has been supported in part through KAUST research fund.

1 V. Intaraprasonk and S. Fan, Appl. Phys. Lett. 98, 241104 (2011).
2 V. Kumar, J. Boley, Y. Yang, H. Ekowaluyo, J. Miller, G. Chi, and J. Rhoads, Appl. Phys. Lett. 98, 153510 (2011).
3 B. DeMartini, J. Rhoads, M. Zielke, K. Owen, S. Shaw, and K. Turner, Appl. Phys. Lett. 93, 054102 (2008).
4 Y. Kessler, S. Krylov, and A. Liberzon, Appl. Phys. Lett. 109, 083503 (2016).
5 Y. Gerson, D. Schreiber, H. Grau, and S. Krylov, Journal of Micromechanics and Microengineering 24, 25008 (2014).
6 X. Huang, M. Manolidis, S. Jun, and J. Hone, Appl. Phys. Lett. 86, 143104 (2005).
7 B. Ilie, Y. Yang, K. Aubin, R. Reichenbach, S. Krylov, and H. Craighead, Nano Lett. 5, 925–929 (2005).
8 D. Southworth, L. Bellan, Y. Linzon, H. Craighead, and J. Papia, Appl. Phys. Lett. 96, 163503 (2010).
9 R. Harne and K. Wang, J. Sound Vib. 333, 2241 (2014).
10 S. Ilyas, A. Ramini, A. Arevalo, and M. Yonius, J. Microelectromech. Syst. 24(4), 1124–1131 (2015).
11 G. Rebeiz, RF MEMS: Theory Design and Technology (Wiley Interscience, Hoboken, NJ, 2003).
12 W. de Groot, J. Webster, D. Felnhofer, and E. Gusev, in IEEE Transactions on device and materials reliability (2009).
13 H. Conrad, H. Schenk, B. Kaiser, S. Langa, M. Gaudet, K. Schimmann, and M. Lenz, Nature Communications 6, 10078 (2015).
14 D. Peroulis, S. Pacheco, K. Sarabandi, and L. Katehi, in IEEE Transactions on microwave theory and techniques (2003), p. 259.
15 J. Huang, K. Liew, C. Wong, S. Rajendran, M. Tan, and A. Liu, Sensors and Actuators A: Physical 93, 273 (2001).
16 H. Hosaka, K. Ito, and S. Kuroda, Sensors and Actuators A: Physical 49, 87 (1995).
17 W. Van Spengen, R. Puers, and I. De Wolf, Journal of Micromechanics and Microengineering 12, 702 (2002).
18 A. Eichler, J. Chaste, J. Moser, and A. Bachtold, Nano Letters 11, 2699 (2011).
19 R. Karabalin, X. Feng, and M. Roukes, Nano Letters 9, 3116 (2009).
20 I. Mahboob and H. Yamaguchi, Appl. Phys. Lett. 92, 173109 (2008).
21 N. Jaber, A. Ramini, and M. Yonius, Microsystems & Nanoengineering 2, 16002 (2016).
22 A. Ramini, A. Ibrahim, and M. Yonius, Microsystem Technologies 22, 1967 (2016).
23 N. Jaber, A. Ramini, Q. Hennawi, and M. Yonius, Sensors and Actuators A: Physical 242, 140 (2016).
24 F. Alsaleem, M. Yonius, and H. M. Ouakad, Journal of Micromechanics and Microengineering 19 (2009).