Compact Tunable Resonators using Vertically-shaped Comb-fingers Towards Vibration Energy Scavenging

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Abstract

We report, for the first time, the development of compact tunable comb-drive resonators that use vertically-shaped comb-fingers as electrostatic springs towards improved frequency matching within vibration energy scavengers. Bi-directional tuning >17% of the resonant frequency and electrostatic spring constants up to 1.19 N/m @70V have been achieved without increasing device size. The influence of vertically-shaped comb-finger geometry on electrostatic spring strength and linearity has been evaluated.

Keywords: Vibration Energy Scavenging, tunable resonators, gray-scale technology

1. INTRODUCTION

Energy scavenging has become an active topic of research in MEMS and wireless sensor networks for applications requiring node lifetimes beyond the capabilities of traditional batteries [1]. Groups have already demonstrated wireless RF transmitters with 10m range consuming <1mW that rely solely on solar and vibrational scavenged energy [2]. Yet, generic models show that the power available through vibrational energy scavenging is radically reduced when the resonant device is poorly matched to the frequencies of ambient vibrations (typically hundreds of Hz) [3]. Furthermore, the output power available through a resonant generator also depends on the damping factor, where low damping leads to higher power at the cost of being more frequency selective. One must also be cognizant that the frequency and acceleration of ambient vibrations will be specific to each environment, and may change over time. Thus, the ability to tune the frequency resonant generators is attractive for maximizing output power.

Multiple MEMS tuning approaches have been investigated for creating electrostatic springs to modify the effective spring constant of a resonant system, including: parallel-plate [4], fringing field [5], and variable gap comb-drives [6]. Of these systems, only the variable gap comb-drive approach showed operation over large oscillation amplitudes (~10μm). However, this ability comes at the cost of significantly increasing the area required for a single comb-pair, leading to reduced finger density and overall electrostatic spring strength. In contrast, this research presents an alternative approach using vertically-shaped comb-fingers (see Figure 1) to create electrostatic springs in silicon without increasing
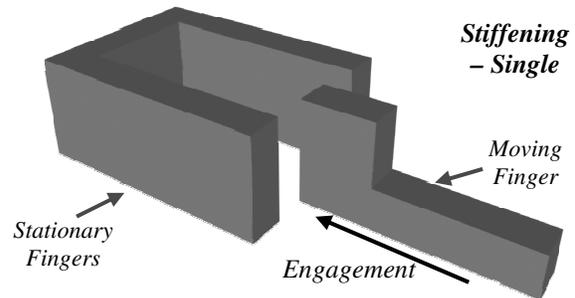

Fig. 1: Vertically-shaped comb-resonators can create electrostatic springs without increasing device size.

device area. This capability is made possible by the recent development of a 3-D silicon fabrication technique called gray-scale technology [7,8].

2. DESIGN AND SIMULATION

To understand the principles of the tunable comb-resonators in this research, it is easiest to look at the standard force relationship in electrostatic comb-drive actuators:

$$F = \frac{1}{2}V^2\frac{\partial C}{\partial x} \approx \frac{N \cdot \varepsilon_0 \cdot height}{gap}V^2 \qquad (1)$$

where V is the applied voltage, N is the number of comb-fingers, and ε_0 is the permittivity of free space. Eq. (1) is an approximation for comb-finger geometries of constant height and gap, in which case the force is independent of comb-finger position (or engagement). However, by designing the capacitance vs. position profile to include

changes in gap and/or height, the electrostatic force vs. position would change as well, creating an electrostatic spring, k_{elec}. Since standard MEMS fabrication is limited to planar structures, the easiest method to create an electrostatic spring is therefore to change the gap with position, which dramatically decreases the comb-finger density. In contrast, vertical shaping of the comb-finger enables a more compact electrostatic spring.

During operation, the generated k_{elec} combines with the mechanical spring constant, k_{mech}, to create the effective spring constant (k_{eff}) of the system, thereby modifying the resonant frequency of the overall structure:

$$f_{tuned} = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m}} = \frac{1}{2\pi}\sqrt{\frac{k_{mech} + k_{elec}}{m}} \quad (2)$$

which can also be expressed in terms of the original, un-tuned, resonant frequency, f_0:

$$f_{tuned} = f_0\sqrt{1 + \frac{k_{elec}}{k_{mech}}} . \quad (3)$$

The simplest vertically-shaped comb-finger design has a single step, as shown in Figure 1. Since comb-drive force is proportional to dC/dx (i.e. height), short parts of the finger produce less force than tall parts. The transition between these two regions (change in force over distance), acts as the electrostatic spring (k_{elec}). For the case shown previously in Figure 1, the electrostatic force is initially large, and then decreases as the fingers engage. The electrostatic force essentially "helps" the shuttle deflect more in the beginning of finger engagement, than at the end. Thus, the spring would appear to be "stiffer" than the mechanical spring constant alone ($k_{eff} > k_{mech}$), so the resonant frequency will increase and k_{elec} is taken as a positive number according to Eq.'s (2) and (3). Conversely, a "weakening" spring can be accomplished by creating a comb-finger that grows in height as the
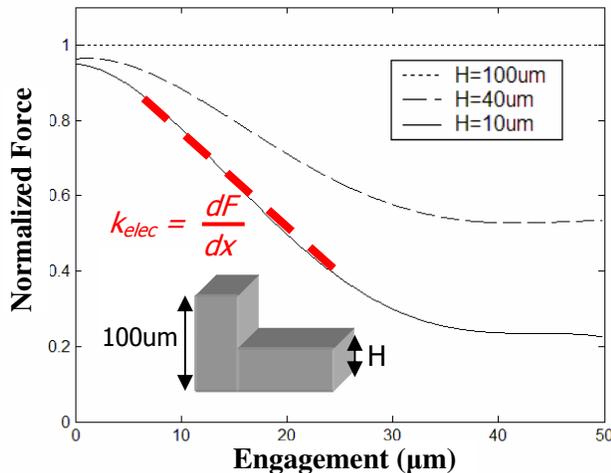
fingers engage, leading to negative k_{elec} values and decreased resonant frequencies.

Finite element analysis was performed in FEMLAB using 3-D models of our designs in order to account for fringing fields. Of particular interest was investigating the effects of different geometries on the generated capacitance profiles and subsequent electrostatic forces. Example simulations are shown in Figure 2 assuming a 10μm gap and 100μm maximum finger height – note how the transition between the large and small force regions creates a quasi-linear k_{elec}. Three primary comb-finger designs were explored: one had fingers that increase in height as they engage, creating a "weakening" k_{elec}, while two ("single" and "double") had fingers that decrease in height as they engage, creating "stiffening" k_{elec}'s. "Single" designs contained a single step on the stationary comb-fingers, while the "double" design had steps on both moving and stationary fingers.

The resonators designed and fabricated in this work follow the conceptual layout shown in Figure 3, where a single proof mass, or shuttle, is suspended between two electrodes by mechanical springs. The electrode with variable-height comb-fingers must then receive a DC tuning voltage to create the electrostatic spring. The opposite electrode (with only planar fingers) receives an AC signal that is swept in frequency to obtain the frequency response of the system using a stroboscopic measurement system (Veeco NT1100).
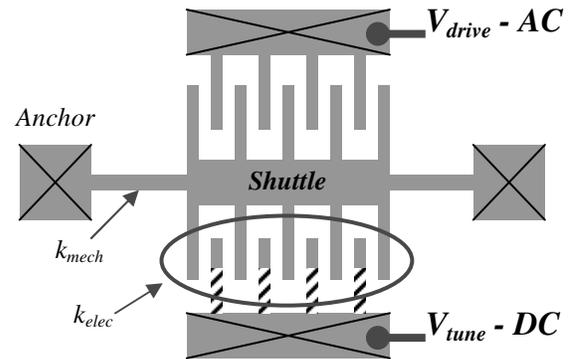

Fig. 3: Conceptual layout of MEMS tunable resonators fabricated and tested using variable height comb-fingers as electrostatic springs.

3. FABRICATION AND TESTING

Compact vertically-shaped silicon resonators were fabricated on p-type silicon-on-insulator (SOI) wafers with a 100μm thick device layer and a 2μm thick buried oxide. The optimization of gray-scale technology and its integration within an electrostatic actuator process flow has been described elsewhere [7,8]. An SEM of fabricated vertically-shaped comb-fingers exhibiting a single gray level is shown in Figure 4.
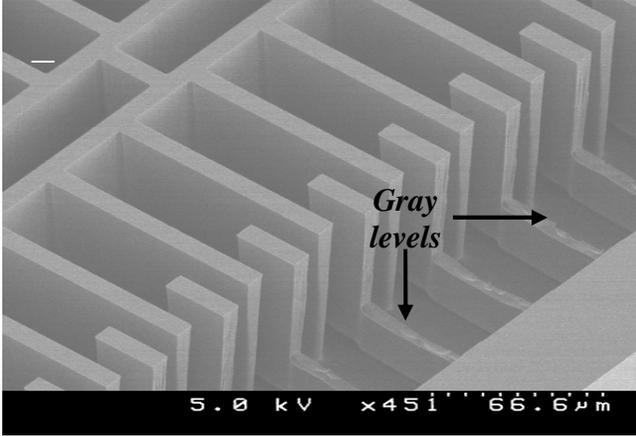

Fig. 2: Simulated force vs. engagement for finger designs with gray-level heights, H, of 10, 40, and 100μm (planar).

Fig. 4: *SEM of fabricated tunable comb-resonators with a single step that creates a "stiffening" electrostatic spring.*
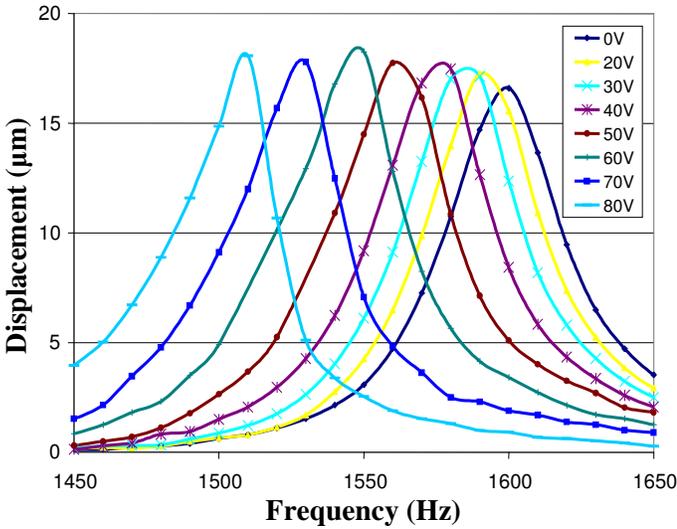

Fig. 5: *Measured resonant peaks for different DC tuning voltages in the "weakening" design.*
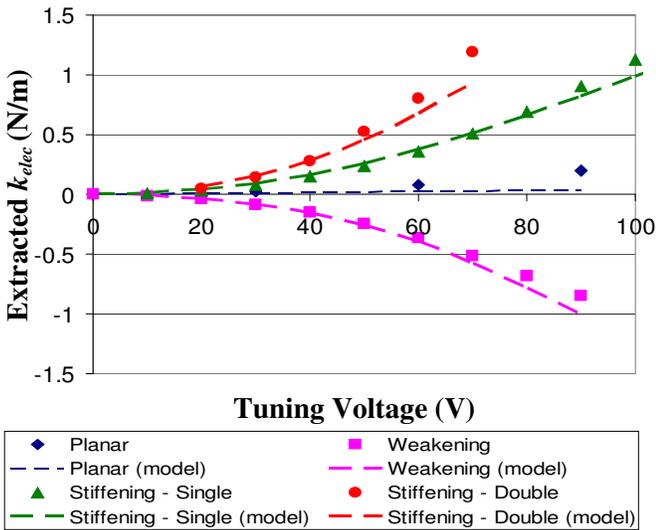

Fig. 6: *Modeled and extracted electrostatic spring constants.*

Static tests of displacement vs. voltage on the planar drive side were used to determine the mechanical spring constant (k_{mech}). The stroboscopic system was then used to measure the un-tuned resonant spectrum as a function of drive frequency, and a Lorentzian fit used to find the peak frequency (f_0). The DC tuning voltage was then increased and the resonant spectrum measured again. Example resonant peaks for different DC tuning voltages are shown for a "weakening" device in Figure 5, where the original frequency is near 1600 Hz and the tuned frequency approaches 1500 Hz when $V_{tune} = 80$ V.

The effective electrostatic spring constant for each tuning voltage was then extracted from the associated resonant peak for the "weakening" and both "stiffening" designs (see Figure 6). Measured values of k_{elec} agree well with those derived from simulations of the capacitance-engagement profile. The largest k_{elec} was achieved using the "stiffening – double" design where the change in force with position is most dramatic, achieving up to 1.19 N/m @ 70V. The magnitude of frequency tuning then depends on the relative strength of k_{elec} and k_{mech} (see Eq. 3), where the 1.19 N/m electrostatic spring resulted in tuning of the resonant frequency by $>17\%$ f_0.

4. DISCUSSION

While the previous tests confirm the proposed electrostatic resonant frequency tuning, it was observed that measurements using large drive amplitudes exhibited some non-linear behavior. Shown in Figure 7 are multiple frequency sweeps on a "weakening" device using $V_{tune} = 80$V but with different drive voltages, and therefore vibration amplitudes. At low drive voltages, the peak resides near 1470 Hz, but as the drive voltage increases, the peak "bends" towards the un-tuned resonant frequency by ~50 Hz. This non-linear behavior is characteristic of 3rd-order stiffness coefficients in the Duffing equation [4]:

$$m\ddot{x} + \xi\dot{x} + kx + \gamma x^3 = b\cos(\omega t) \qquad (4)$$

where

$$F = kx \pm |\gamma| x^3 \qquad (5)$$

where m is the resonating mass, ζ is the damping coefficient, and γ is the 3rd-order spring constant. Depending on the sign of γ, the resonant peak can bend towards either higher or lower frequencies, acting as a "hard" or "soft" spring, respectively.

FEMLAB simulations showed this behavior to be an artifact of the single step comb-finger design, where the change in force vs position (dC/dx) is only approximately linear (see Figure 2). If we instead look at k_{elec} vs position (d^2C/dx^2), we find that a single step design makes k_{elec} highly position dependent (see Figure 8). Thus, large amplitude vibrations "see" a different k_{elec} depending on the position of the resonator, causing an asymmetric

resonant peak. In our case, the peak bends back towards the un-tuned resonant frequency because the effective tuning provided by the electrostatic spring tuning is being reduced. However, since gray-scale technology is being used to fabricate these devices, it would be possible to incorporate comb-finger designs with multiple vertical steps. Further simulations show that a design with 4 gray levels could radically reduce such non-linear stiffness coefficients, as shown in Figure 8.
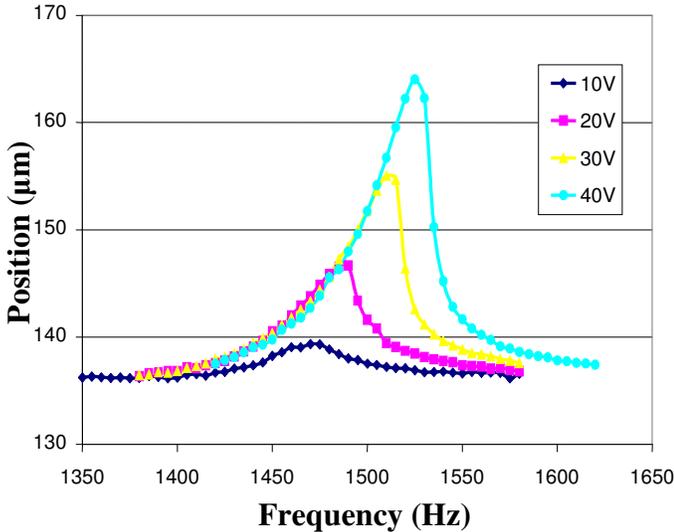

Fig. 7: *Non-linear stiffness coefficients appear when vibration amplitude increases for a fixed $V_{tune} = 80\ V$.*
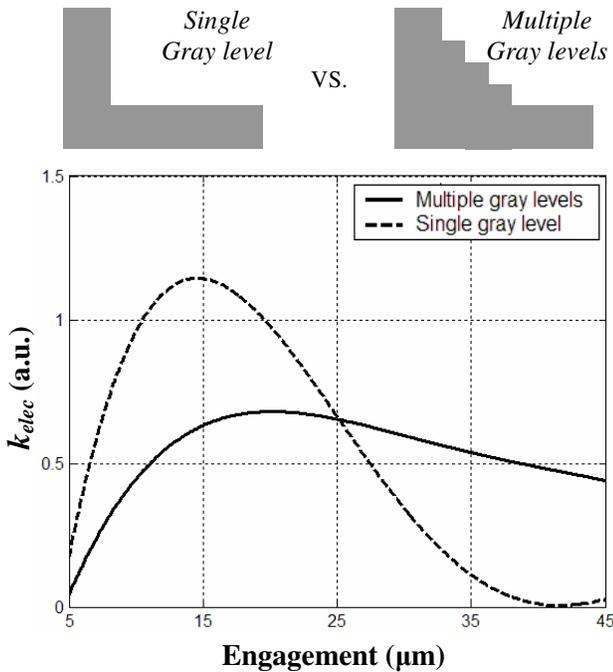

Fig. 8: *Simulations show that comb-finger designs using multiple gray-levels could create electrostatic springs that change less with position, reducing non-linear behavior.*

5. CONCLUSION

We have demonstrated compact vertically-shaped comb-resonators capable of bi-directional resonant frequency tuning. Electrostatic spring constants up to 1.19 N/m @ 70V and resonant frequency tuning by >17% f_0 have been achieved without increasing device size. The design and fabrication techniques presented here could provide the critical ability to optimize the resonant frequency of vibration energy scavenging nodes for specific ambient environments, thereby maximizing potential scavenging power.

Future work should concentrate on further development of multi-level comb-fingers for reducing non-linear stiffness coefficients, as well as the integration of an on-chip tuning mechanism and associated power electronics.

6. ACKNOWLEDGEMENTS

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