Self-Excitation in Electrostatically Actuated Non-Identical Coupled Curved Microbeams

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***Summary*— We report on an experimental demonstration of an open-loop self-excitation (OPSE) response in a microstructure composed of two initially curved and non-identical microbeams. One of the beams faces the electrode (beam #1), exposing it to displacement-dependent electrostatic loading, whilst the second beam (beam #2) experiences a "mechanical", displacement-independent emanating from a truss set in between the two beams. The SE is triggered at high voltages, where one would expect to encounter a pull-in (PI) response. However, the presence of an SE appears to prevent a PI towards the electrode from occurring. The existence of an SE response, which can occur, regardless of any added modification to the circuit, suggests that such a response is an intrinsic feature of the microstructure.**

Keywords—Pull-in; Quasi-static loading; Electrostatic actuation; MEMS/NEMS

I. Introduction

Self-excitation (SE) in micro/nanoelectromechanical systems is usually achieved when a form of closed-loop control is added [1,2], changing the actuated voltage according to the measured response, thereby producing virtual damping. This effect is of fundamental scientific interest and has been employed in applications such as timing and frequency control [3], energy harvesting [4,5], sensors [2,6] and atomic force microscopy [1]. However, these examples rely on embedding the beam (resonator) in a feedback loop of an oscillator circuit with positive feedback criteria, satisfied for oscillation start-up and ultimately, transitioning to steady-state behaviour due to some form of engineered nonlinearity (e.g. automatic gain control in a sustaining amplifier). Three examples, however, stand from the rest, since these do not necessitate closed-loop control. The first entails an energy harvester composed of a beam resting between an air chamber with air flowing inside and ambient soundings. The dynamic air pressure acting on the beam results in a flutter-type instability, a type of self-excited response [5]. Another example is that of micromachined thermal-piezoresistive oscillators describing a type of self-excitation in heated microstructures due to the intrinsic feedback between the thermal and mechanical domains [7]. The third and most similar example of an OPSE was achieved in a bistable curved micro beam. However, the response was attributed to the coupling between the beam and the circuit [8]. More specifically, the response evidenced itself when a large enough resistor, having a value of $\approx 1\text{M}\Omega$, was placed in-series between the beam and the power source. Its presence prompted a change in the time constant of the circuit, delaying the response of the beam after snap-through, causing it to snap back and forth between two equilibria. In the current study, we show a microstructure composed of two curved beams, which can achieve OPSE regardless of any external circuit components. In so doing, one can attain such a singular response in a simple beam-circuit design.

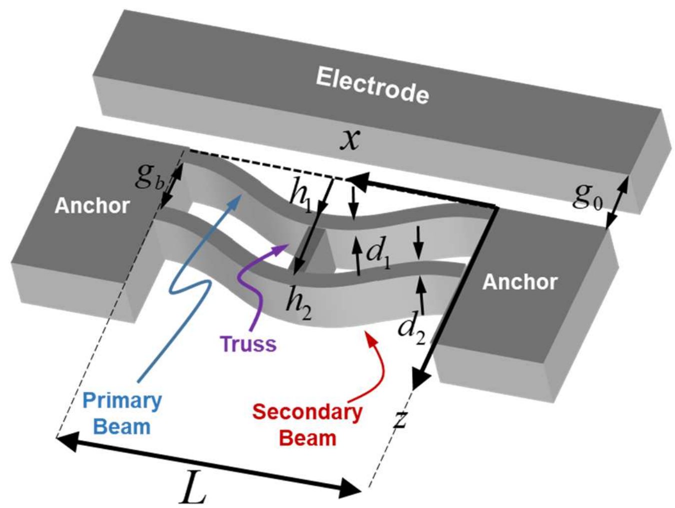

Figure 1: Schematics of initially curved coupled microbeams, marked as beam #1 (primary beam) and #2 (secondary beam), with elevations h_1, h_2 thicknesses d_1, d_2, width b and length L, actuated by a close gap electrode located at a distance g_0. The length g_b marks the distance between the edges of the beams. The midpoints of the beams are joined by a truss, coupling the two.

II. Methods

A microstructure composed of length L and width b, is constructed two initially curved beams of marked as beam #1 and #2, each having its own defining elevation (h_1 and h_2) and thickness (d_1 and d_2), are separated by length g_b at their respective edges. The beams are coupled by a truss located at the midpoints of the beams, with beam #1 located at a distance g_0 from an electrode (Fig. 1). Actuation of the structure is carried out via beam #1, affectively driving the microstructure

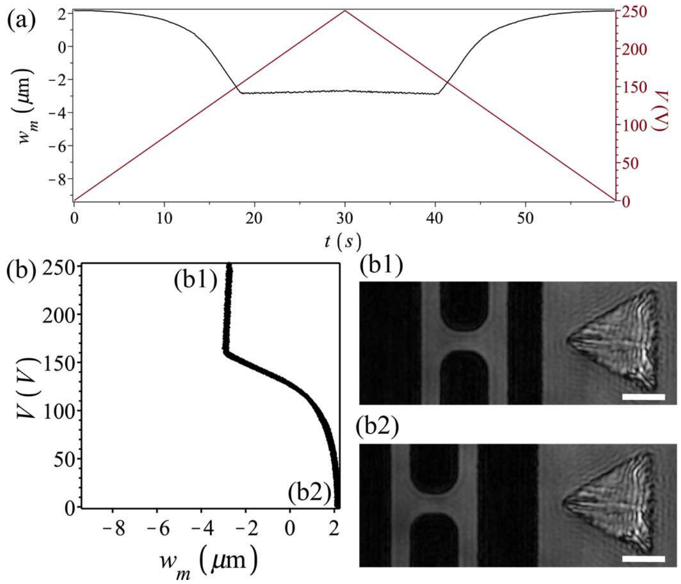

Figure 2: (a) Time history showing the location of the structure's centre when driven by a triangular waveform, composed of 30 s increasing ramp, followed by 30 s decreasing ramp, with a maximum voltage of V_{max} = 250 V. The time history (in black) is juxtaposed against the input signal (in red). (b) Equilibrium curve, extracted from the time history. (b1), (b2) Snapshots of the centre of the structure, corresponding to V=250 V and 0 V, respectively.

due to the interaction between the beam and the electrode, situated directly below it. For this reason, we dub beam #1 as the "Driving Beam", while beam 2# is dubbed as the "Secondary Beam", all because it responds to the first and does not directly encounter the electrode. By interplay of the parameters which define the structure, it can cross a threshold which prompts bistability [9,10], namely the existence of two equilibria under the same load [11]. Having mentioned that, it is important to note in the present case, the structure is set below its bistability threshold, and therefore is not bistable and is expected to have a single limit point, the pull-in point. The device-under-test reported on in the present work is fabricated using a SOI-MEMS process (SOIMUMPs). For static characterisation, the structure is first quasi-statically driven with a triangle load, composed of an increasing ramp, followed by a decreasing one, each having a time span of 30 seconds. The static experiment was recorded via Lyncée Tec digital holographic microscope (DHM). To process the recordings, an edge detection technique was used to visually track the midpoint of the microstructure (for details see [12]). Since the goal is to statically characterise the microstructure, the recording frame rate was set for ≈10 fps, prompting the time history and equilibrium curves in Fig. 2(a) and (b), respectively, for a double beam with L≈1000 μm, b≈25 μm, d_1=(3.26±0.15) μm, d_2=(3.42±0.15) μm, h_1=(2.17±0.15) μm, h_2=(1.25±0.15) μm g_0=(9.33±0.15) μm, g_b=(10.26±0.15) μm. With the evidence of an OPSE, the microstructure was then actuated with a trapezoidal signal, having a constant voltage between and increasing and decreasing ramps, to visualise a qualitative difference in behaviour with rising voltage. Finally, to

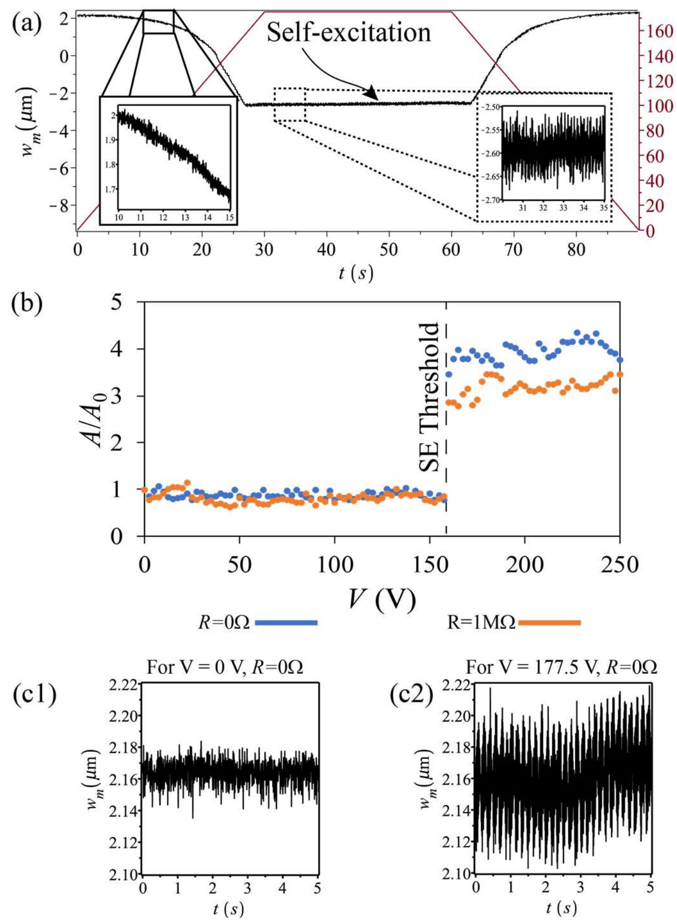

Figure 3: (a) Trapezoidal signal with a maximum of V_{max}≈175V and no additional in-series resistance (i.e., R=0Ω), depicted in red and juxtaposed against a time history of the beams structure when introduced to 30 seconds constant voltage, set between 30 seconds increasing and decreasing ramps showing a small increase in amplitude in the constant segment. Two insets are show responses in two different locations on the plot, when the voltage rises and when the structure is at self-excitation mode in solid and dashed rectangles, respectively. (b) Ratio of average amplitude gain (A/A_0) registered at each voltage, against amplitude registered under zero voltage (A_0) for two different circuit configurations: R=0Ω and R≈1MΩ in blue and orange, respectively. Vertical dashed line represents the SE threshold. (c1), (c2) Time histories of location amplitude registered when introduced to 0 and 177.5 V DC voltages, respectively.

characterise the SE and find its threshold, incremental DC voltages were introduced to the microstructure, from 0 to ≈250 V, with increments of ΔV ≈ 25V, showcasing amplitude evolution as a function of the voltage. Each recording possessed one thousand frames, and was recorded at a frame rate of ≈192 fps. Note that while the frequency of the response could not be estimated under such a frame rate, the boundary of the response is clearly visible. To get a clear measure of the amplitude (A), it was averaged for the duration of each run and normalised against a zeroth amplitude (i.e., the amplitude observed at zero voltage, A_0), prompting the gain $A/A_0=f(V)$. All experiments were carried out using an arbitrary waveform generator and a x25 amplifier. To witness the effect, of additional resistance, the incremental voltage experiments was carried out twice. First for without any additional resistance (i.e., R=0), and another one with an added in-series resistor, having a value of R=1MΩ.

III. Results and Discussion

Figure 2 shows time history and equilibrium curve of the structure, depicting its midpoint location, w_m, showing that it encounters a plateau at ≈ 160V, whilst the voltage still increases, avoiding or delaying a pull-in. Converting the time history to an equilibrium curve [12] confirms that the structure is approaching its pull-in point due to its proximity to the electrode, as exempted by the two snapshots in (b1) and (b2), corresponding to 0V and ≈250V, respectively, but does not reach it. The following trapezoidal actuation signal shows a clear increase in amplitude at ≈175V in Fig. 3(a). To isolate the threshold, at which SE occurs, it was characterised via incremental rising voltage, given in Fig. 3(b). The result presents a quantifiable jump in amplitude, granted at V≈160V for the two in-series resistance values, R=0Ω and R=1MΩ, depicted in blue and orange, respectively. For R=0Ω, an average gain of A/A_0≈3.459 is achieved, while an overall increase in amplitude is visible, culminating in a value as high as A/A_0≈4.348 at V≈ 277.5V. Note that while we cannot ascertain as to the frequencies present in the response, we can witness a difference between the noise under 0 V (c1) and a noticeable response at ≈177.5 V (c2). For R≈1MΩ, smaller gain values are achieved, with a sudden increase in amplitude ratio, prompting A/A_0≈ 2.871 at V≈160V, and a maximum value of A/A_0≈3.473 at V ≈250V. Such an observation shows that the phenomenon is independent on added resistance. However, additional resistance will, in turn, add electrical damping, causing a decrease in self-excitation overall gain.

IV. Conclusions

In this study, we have shown that it is possible to instigate an OPSE response in a coupled double beam microstructure. The occurrence of a such a response without additional circuit components leads allows us to deduce that such a response is an intrinsic property of the microstructure, thereby promoting simpler circuit designs and smaller footprints and as such, further miniaturisation. Such observations can promote the usage of double microbeams in voltage and/or frequency converters and transducers, pseudo-random number generators etc.

Acknowledgments

L.M. acknowledges the support of the Blavatnik Postdoctoral Research fellowship. Thanks for Madan Parajuli and Dr. Guillermo Sobreviela for their help with the experimental setup.

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