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Suppression of the A-f-mediated noise at the top bifurcation point in a MEMS resonator with both hardening and softening hysteretic cycles

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We study the nonlinear behavior of a microelectromechanical resonator implemented using the SilTerra MEMS on CMOS platform. The resonator shows, in a same frequency response, two hysteretic cycles of different origin: mechanical and electrical. We observe that, by increasing the resonator DC voltage, the resonator goes from having a purely mechanical (hardening) nonlinear response to a purely electrical (softening) one, experiencing a mixed regime where mechanical and electrical nonlinearities coexist and partially compensate. We explain how the compensation between nonlinearities can be used to improve the phase noise of an MEMS-based oscillator. Specifically, we show that it is possible to operate the resonator at the top bifurcation point, while at the same time suppressing the amplitude-mediated frequency noise.

1. Introduction

Quartz crystal resonators have been one of the main elements in radio frequency (RF) applications during the last century. Nowadays, however, they are failing to keep pace in the ongoing and permanent race towards miniaturization that the microelectronics industry is running. Resonant microelectromechanical systems (MEMS) are one of the main candidates to replace quartz crystal resonators in applications such as filtering, signal processing, and time keeping [1–4]. This fact has motivated, among other applications, the investigation of MEMS resonators in the recent decades. This intensive research has been successful in a wide range of objectives. For instance, it is currently possible to integrate MEMS resonators into complementary metal-oxide-semiconductor (CMOS) technology [4–8], reducing its size and manufacturing cost. Also, MEMS resonators with quality factors that are competitive with those of quartz crystal resonators [9] and MEMS-based oscillators that meet the Global System for Mobile Communications (GSM) specifications [10–13] have been reported, overcoming the lack of performance of early MEMS oscillators. Other initial disadvantages of MEMS resonators and oscillators such as their temperature stability have also been overcome; passive [14] and active [15] methods to increase the temperature stability have been developed to overcome this drawback. Another early problem such as the high voltages needed for biasing the MEMS resonators – in order of the tens of volts – has been addressed. For instance, low-voltage CMOS-MEMS oscillators with biasing voltages down to the power supply voltage of the circuit have been demonstrated [5].

Nonetheless, the miniaturization of MEMS resonators has led to the rise of new challenges. For instance, the influence of the thermo-mechanical noise increases due to the reduction of the dimensions and mass of resonators, increasing their motion fluctuations [16]. Also, in these so called nanoelectromechanical systems (NEMS) resonators, nonlinear related phenomena appears at lower amplitudes [17,18]. These two phenomena reduce the linear dynamic range – the ratio between the largest and smallest values of a usable linear signal – of resonators.

Nonlinearities in MEMS and NEMS resonators present some drawbacks for the performance of MEMS-based oscillators [19]. However, operating the MEMS resonant element of an oscillator beyond the linear dynamic range, i.e., in the nonlinear regime, can be used to surpass the limits of conventional oscillators [20]. Stable operation of oscillators working with the MEMS resonator beyond the critical operating point – the operating point where the first

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bifurcation points appear – has been demonstrated [21]. In fact, the influence of the resonator's nonlinearities into the phase noise of oscillators is currently a topic under intense study [20–27].

Some of the consequences of the appearance of nonlinearity are:

a The appearance of bifurcation points, i.e., points where the resonator's nonlinear frequency response jumps between two separated branches of stable solutions, allowing multivalued responses [19,28–30].
b The coupling between amplitude A and frequency f, i.e., the A-f effect [31–33]. This coupling can cause the addition of phase noise due to amplitude-induced frequency fluctuations (A-f-mediated noise) [32–37].

The first effect (a) sets the linear power handling capability – the maximum power the resonator can handle before bifurcation occurs [38,39]. The second effect (b) worsens the phase noise of oscillators based on a nonlinear resonator.

In previous works, two strategies based on compensating nonlinearities in MEMS-based oscillators have been demonstrated in order to increase their linear power handling capabilities, reduce the A-f effect, and avoid the A-f-mediated noise. One is based on tuning the resonator DC voltage V_{DC_r} [32–36,40,41]; the other one is based on changing the doping concentration and the crystalline alignment of the resonator [42]. The first strategy rests on the compensation that takes place between the electrical and mechanical nonlinear effects [32–36,40,41,43,44]. The compensation between nonlinearities can be employed to achieve two important objectives in MEMS-based oscillators: to increase the power handling capability – if limited by nonlinearities – and to reduce the A-f-mediated noise. These two different objectives allow improving the phase noise performance of oscillators. Increasing the power handling capability – or in general, the carrier signal delivered to the resonator $\langle P_r \rangle$ – improves the far-to-carrier phase noise. Reducing the A-f-mediated noise improves the close-to-carrier phase noise.

In this paper, we study a CMOS-MEMS resonator whose nonlinear behavior highlights by the appearance of two opposite hysteretic cycles in a same frequency response. The first hysteretic cycle has a hardening behavior and is of mechanical origin. The second hysteretic cycle presents a softening behavior and is of electrical origin. First, the fabrication process and geometry of the resonator are described. Second, we show some experimental measurements that illustrate the four different nonlinear frequency responses that the fabricated resonator can experience. From the experimental characterization, we study the A-f effect and show the existence of some operation points where it is possible to suppress the amplitude-mediated frequency noise. Based on this study, we propose a new optimum operating point located at the top bifurcation point where the A-f mediated noise can be nulled. This point combines the advantages of suppressing the A-f-mediated noise, operating the resonator in a bifurcation point, and a high carrier signal. This point is possible thanks to the presence of the second hysteretic cycle of electrical origin that limits the bending towards high frequencies (towards the right) of the first one of mechanical origin.

2. Resonator description

Several paddle bridge resonators were fabricated on top of a CMOS chip using the Silterra 0.18 μm commercial CMOS technology [7]. The structural layer of the resonators is a bimetallic thin-film – with Young's modulus E = 190 GPa and density ρ = 3860 kg/m^3 – of thickness$h$ = 500 nm. The paddle bridge has a total length of l = 15μm, with 0.5μm arms. The main structure has a width of b = 2.85 μm. A scanning electron microscope (SEM) image shows the device in Fig. 1(a). Two electrodes, with dimensions set by l_i = 0.85 μm, l_f = 14.15 μm, and b_e = 0.47 μm, were fabricated underneath the resonators in order to actuate them. This configuration of electrodes can promote the first flexural (at 12 MHz) or the first torsional (at 24 MHz) modes; however, in this work, we only used the first one. The mode profiles of the first vertical flexural and the first vertical torsional modes can be seen in Fig. 1(b). The nominal gap distance between the movable structure and the electrodes is g = 90 nm. Electrostatic actuation and capacitive detection was used to transduce the MEMS in a two-port configuration [45,46]. The experimental setup to characterize the device is schematically depicted in Fig. 1(c). The 0-level vacuum package allowed the resonators to work at a pressure of 1 mbar. Under such conditions, the characterized resonators reached a quality factor around$Q$ = 1500.

3. Experimental analysis

Electrical measurements at room temperature of MEMS devices as the one shown in Fig. 1(a) were performed using the measurement setup schematically shown in Fig. 1(c). The excitation and sensing electrodes were connected, respectively, to the output (1) and input (A) ports of a network analyzer (Agilent E5100A). An oscilloscope with a 50 Ω input impedance was used in order to experimentally characterize the actuation AC voltage applied to the MEMS resonator and avoid impedance mismatching. The movable structure of the device was connected to a DC power supply. Employing this configuration, we characterized the frequency response of the first flexural vertical mode of several paddle bridge structures. We performed frequency sweeps of duration 90 s, containing each sweep 1801 measurements points, and with an IF bandwidth of 20 Hz. Thus, ensuring the measurement of output power and phase in the stationary state.

3.1. Output power magnitude-frequency responses

Fig. 2 shows some frequency responses taken in order to characterize a paddle bridge resonator applying a resonator DC voltage of $V_{DC_r} = 10V$ and different actuation AC powers. Fig. 2(a) shows the transition of the device response from a linear behavior (low actuation AC powers) to a strongly nonlinear one (high actuation AC powers). In Fig. 2(a), we see that the nonlinear behavior contains phenomena related to both mechanical and electrical nonlinearities [32–36,40,41,43,44]. Mechanical nonlinearities cause a right bending of the frequency response (hardening effect), while a left bending is attributed to an electrical nonlinear effect (softening effect) [36]. Increasing the actuating AC power, we see first that the dominating nonlinearity is of mechanical origin and the frequency response bend towards higher frequencies. Next, we reach the critical point and a clockwise hysteretic cycle of mechanical origin emerges. Then, nonlinear effects of electrical origin start to take place,

changing the bending direction of the frequency response. Finally, we reach what we call a second critical point and a second hysteretic cycle – this time counterclockwise and of electrical origin – appears. Fig. 2(b) details this behavior where, in a same frequency response, two hysteretic cycles coexist.

Fig. 3 shows the four different output power magnitude-frequency response topologies occurring when changing the resonator DC voltage: mechanical-dominant, mixed-double, mixed-single, and electrical-dominant.

For low resonator DC voltages ($V_{DC_r} = 6V$), the dominant nonlinear phenomenon is of mechanical origin. This is the case in Fig. 3(a). We see that increasing the driving power bends the resonance curves towards the right, shifting the resonance frequency f_0 towards higher frequencies and finally generating a clockwise