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A megahertz-frequency tunable piecewise-linear electromechanical resonator realized via nonlinear feedback☆

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ABSTRACT

Vibration-based sensing modalities traditionally have relied upon monitoring small shifts in natural frequency in order to detect structural changes (such as those in mass or stiffness). In contrast, bifurcation-based sensing schemes rely on the detection of a qualitative change in the behavior of a system as a parameter is varied. This can produce easy-to-detect changes in response amplitude with high sensitivity to structural change, but requires resonant devices with specific dynamic behavior which is not always easily reproduced. Desirable behavior for such devices can be produced reliably via nonlinear feedback circuitry, but has in past efforts been largely limited to sub-MHz operation, partially due to the time delay limitations present in certain nonlinear feedback circuits, such as multipliers. This work demonstrates the design and implementation of a piecewise-linear resonator realized via diode- and integrated circuit-based feedback electronics and a quartz crystal resonator. The proposed system is fabricated and characterized, and the creation and selective placement of the bifurcation points of the overall electromechanical system is demonstrated by tuning the circuit gains. The demonstrated circuit operates at 16 MHz. Preliminary modeling and analysis is presented that qualitatively agrees with the experimentally-observed behavior.

1. Introduction

To date, the success of microelectromechanical systems (MEMS) devices can be seen in their widespread adoption across many industries and use as accelerometers, gyroscopes, microphones, and sensors. The importance of these systems stem from their potential to provide low-cost, scalable, and sensitive transducer alternatives based upon a wide variety of modalities. Resonant mode sensing is common in MEMS devices and is founded on correlating changes in the resonant behavior of structures and devices to identifiable parameter changes. Within the realm of mass sensing, traditional methods rely on linear or pseudo-linear sensing techniques, which, in turn, rely on the measurement of shifts in the resonant frequencies of a device to detect changes in the device or environmental parameters. These methods have been successfully used to detect a number of chemical species and other small masses (picograms and smaller in many cases) [1–4], and have also found use in applications such as atomic force microscopy (AFM) [5]. Performing sensing tasks in linear resonant modes of operation with high sensitivity requires care-

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ful system design and may incur significant cost or complexity to implement. For example, it may require phase-locked loops, lock-in amplifiers, or other specialized equipment to perform the measurements and yield the high sensitivity in frequency shift measurement required for modern applications.

Some alternative approaches to linear resonant mode sensing involve using nonlinear phenomena. In bifurcation-based sensing, nonlinear behavior can be used to produce large changes in amplitude response when a mass change threshold is exceeded. Prior work includes the sensing efforts of Kumar, et al. [6,7] which achieved high sensitivity in the detection of gas species, with a tradeoff being that such methods do not measure mass in a quantifiable manner aside from a certain threshold being exceeded (it is a “binary” output at the system level).

Resonator devices capable of operating in a nonlinear regime commonly exhibit Duffing-like frequency responses [8]. These devices exhibit multiple coexisting steady-state solutions (stable and unstable), saddle-node bifurcations, and hysteretic behavior. This behavior stems from the specific physical design of the system, where driving the device beyond its standard operating region can result in the nonlinear behavior becoming significant [7]. Unfortunately, higher drive amplitudes require higher power circuitry, reducing applicability for battery-powered, low power, mobile sensing. It is possible to compensate for this by redesigning devices specifically for bifurcation-based sensing, but this may not be practical for all applications.

A promising approach for addressing the issue of excessive drive requirements is to use feedback to produce bifurcation behavior at low drive amplitudes without risking the device’s reliability and lifespan. Some prior work in this area [9] has used a bistable system structure rather than that of a Duffing resonator, but also had the disadvantage of the actuation of the vibration being non-collated. Bajaj, et al. [10] previously demonstrated a collocated sensing and actuation Duffing-like resonator using cubic feedback for the purpose of bifurcation-based sensing using quartz tuning forks, which operated at 32.7 kHz, successfully demonstrating bifurcation-based detection of a change in humidity. Additionally, nonlinear feedback methods have been suggested for use in MEMS devices in past work; these works generally focused on the reduction or mitigation of nonlinear behavior, improving performance, and widening operating regions [11–13]. The majority of such efforts have been performed in simulation or on relatively low-frequency macro-scale analogs of MEMS devices.

In order to implement cubic feedback at 32.7 kHz with minimal phase delay, Bajaj, et al. [10] implemented an analog multiplier-based design. The demonstrated circuit is not applicable for resonators with resonant frequencies above approximately 200 kHz due to the bandwidth of the selected multiplier integrated circuit (IC). This is a critical limitation, as many candidate resonators that have higher sensitivity performance than the tuning forks (for example, the quartz resonators often used in quartz crystal microbalance systems) operate in a higher frequency range (10’s of MHz or higher).

Increasing the functional operating frequency of such a design into the 10’s of MHz range requires the consideration of a number of factors. Chief amongst these factors is phase delay, the impact of which becomes more relevant as frequency increases. In a feedback system, phase delay and group delay through ICs can be represented as a time delay applied to the feedback term. In order to study the effect of this time delay, increasing delay was applied to a model of a cubic feedback system incorporating a 16 MHz quartz resonator (a suitable candidate due to its sensitivity for vapor sensing). The resonator is a Bulk Acoustic Wave (BAW)-type quartz crystal (the mass sensitivity of the resonant frequency of which has been characterized in prior work [14]) with the same operating principle as traditional, well-studied quartz crystal microbalance (QCM) sensors [15,16]. Due to its sensitivity, this resonator can be useful in some mass sensing applications. The resonator was simulated in a feedback loop with ideal amplification and a cubing function, with a time delay in the cubic feedback path. In Fig. 1, the simulation results indicate that the desirable attributes of the Duffing resonator frequency response (namely, the bifurcation-

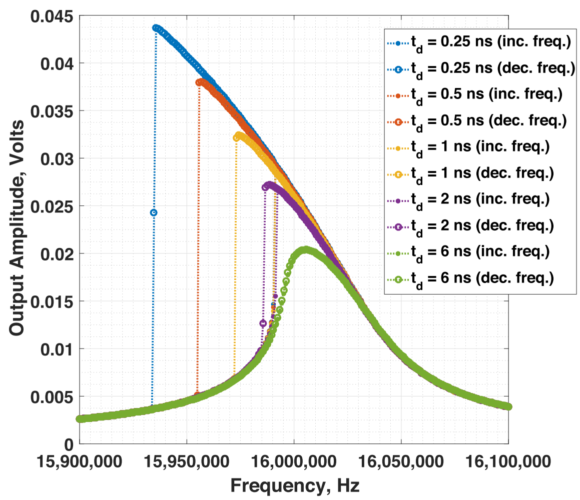

Fig. 1. The simulated effect of increasing time delay on the swept sine response of a Kyocera CX3225 resonator with a nonlinearity consisting of a time delayed cubic feedback. The CX3225 resonator simulated has parameters akin to those listed in Table 1 with an ideal cubic function $f(x) = x^3$ between input and output gains, scaled to produce the bifurcation behavior indicated here.