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Design and characterization of a monolithic CMOS-MEMS mutually injection-locked oscillator for differential resonant sensing☆

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ABSTRACT

This paper presents a proof of concept of a differential sensor based on the phase-difference of two injection-locked MEMS resonators, strongly coupled through their actuation voltages by a digital mixer. For the first time the feasibility of a fully monolithically co-integrated CMOS-MEMS differential resonant sensor, exploiting the capabilities of the injection-locked synchronization is proved. The principle of the system is first presented, from which optimal design guidelines are derived. The design of the different blocks of the system is then addressed. Our experimental results demonstrate the sensitivity enhancement of the proposed solution, as predicted by theory, and partial thermal drift rejection in a 70 °C range. The simulated and experimental results highlight the critical points of the system design, on which the emphasis of this article is placed.

1. Introduction

Resonant sensors [1] exploit the sensitivity of the natural frequency of a mechanical structure to the physical quantity to be sensed (the measurand). As in every sensor, the sensitivity to the measurand must be maximized, and the sensitivity to every other external parameter (noises and drifts) minimized or compensated. Although MEMS resonators have several features making them attractive for VLSI resonant sensing applications (reduced size, large quality factor Q [2]), their sensitivity to temperature, through thermal softening and thermal expansion, is an issue, leading to natural frequency shifts that are not related to the physical quantity to be measured. The natural frequency drift of a MEMS resonator may be compensated if temperature is accurately measured with a separate thermometer, or if a differential sensing scheme is used.

VLSI-compatible thermometers may be implemented either in the CMOS part or in the MEMS part of the system. However, the resolution of state-of-the-art CMOS-compatible thermometers (e.g. based on bipolar junction transistors [3], or inverter chains [4]) is between 20 mK and 1 K [5] which is poor compared to thermistor-based solutions, and might not be sufficient to match the frequency stability standards [6]. Furthermore, the CMOS part of the system may not be at the same temperature as the MEMS resonator, which is another source of inaccuracy. Better resolution (20 μK in [7]) can be achieved by using another MEMS resonator [8,9] or another mode of the same resonator [10,11] as a dedicated thermometer. The temperature data is then used to correct the frequency of the MEMS resonant sensor and enable drift-free sensing. However, frequency correction requires careful calibration of both resonators/modes, in order to determine their precise temperature coefficients, and entails added cost and complexity to the system development.

Alternatively to these approaches, or to complement them, one may use a differential sensing scheme, in which two similar MEMS oscillator loops are used, with the same environmental conditions, hence the same drift (thermal or otherwise), but different sensitivities to the measurand [8]. However, getting two oscillation loops with similar frequencies to operate independently while in close proximity may prove challenging, because of adverse electrical/mechanical coupling phenomena [9]. Note that proper electrical and mechanical isolation may suppress spurious couplings between two oscillator loops. However, whatever form this isolation takes, it must also be designed to minimize temperature

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gradients and dispersions, or drift will not be properly rejected. We think that these design objectives (achieving high electromechanical isolation, with low thermal isolation and little dispersion) are somehow in contradiction and may be difficult to achieve at the same time. The present paper explores an alternative differential resonant sensing scheme, based on the synchronized operation of two resonators, as first introduced in [12] and analyzed in [13], that is *enabled by coupling rather than being limited by it*. We demonstrate for the first-time the feasibility of this concept in a VLSI-compatible approach, using monolithic CMOS-MEMS co-integration in a standard process. This work aims at filling a gap between dual-mode sensors (with more demanding circuit and resonator design, but better temperature rejection) and uncoupled oscillators (with more straightforward circuit design, best measurement range, but poorer temperature rejection).

The outline of the paper is as follows: several solutions for differential resonant sensing are described in Section 2, leading to the investigation of architectures based on synchronized resonators. In Section 3, the properties of the chosen architecture are described from a system-level perspective, along with the design constraints they entail. Section 4 explains how these constraints can be met through chip design, and co-integration of the CMOS-MEMS synchronized oscillator. In section 5 our experimental results are presented, and compared to the theoretical predictions. Section 6 contains some concluding remarks and perspectives.

2. Differential resonant sensing solutions

The most straightforward approach to differential resonant sensing is to design two nominally-identical resonators with similar natural frequencies, the same thermal drift, but different sensitivities to the measurand. For example, one resonator undergoes compressive axial stress when an acceleration is sensed, whereas the other is subject to (opposite) tensile axial stress. Each resonator is placed in a separate oscillation loop: the difference of the individual oscillation frequencies is then theoretically drift-free. This approach has been successfully implemented in [8] and more recently in [14] for temperature compensation in accelerometers. As mentioned in Section 1, drift is properly eliminated only if the two resonators are at the same temperature. The main design challenge of this approach is then to have two separate oscillation loops in close proximity to each other, in order to minimize thermal gradients, and to avoid detrimental phenomena caused by parasitic (electrical or mechanical) coupling [9]. In fact, coupling may induce frequency-locking of the oscillator loops [15–17], which would translate as a dead zone in the sensor response. This issue may be circumvented by using resonators (or resonator modes) with very different natural frequencies [18,19] but this comes at the cost of added system complexity and more calibration steps.

Two alternatives to the previous approach have recently emerged. The first one relies on mode-localization phenomena in coupled resonators [20]: it is extensively reviewed in [21]. In this approach, two (or more) nominally-identical resonators are voluntarily coupled through a mechanical [22] or electrostatic [20,23] restoring force, that is small compared to the intrinsic restoring force of each resonator. This passive coupling scheme leads to energy transfer between them, and to a mode-localization phenomenon that can be used for sensing. For example, the ratio of the modal amplitudes of two weakly-coupled resonators provides a highly-sensitive measurement of the natural frequency mismatch of the resonators [24], which was theoretically and experimentally proved to be drift-free [25]. The sensitivity of this technique is theoretically (limited to) Q times that of a conventional resonant sensor, yet it can be shown that this larger sensitivity entails no resolution enhancement [26]. Although this approach is drift-free, and takes advantage of couplings rather than being hindered by them, it has a few limitations. First of all, it relies on amplitude measurements and therefore requires high resolution analog-to-digital converters (although other output metrics than amplitude ratios may be used [24]). Furthermore, as considered in [25], it is an open-loop technique that requires that an external excitation signal be swept over a frequency band of interest, with unavoidable penalties in terms of response time, although solutions for closing the loop have recently been investigated [27,28].

The other emerging alternative is to synchronize two oscillators through active coupling, and exploit the properties of the resulting phase-locked system to perform drift-free sensing. Active coupling was also studied for its benefits in term of phase noise reduction for clocking or sensing applications in [17,29,30]. It has also been used for bias cancellation of gyroscopes in [31]. In this approach, the resonators are coupled through their actuation voltage, so that they are in a state of mutual injection. Provided the natural frequencies are well-matched (as explained in Section 3), the two-resonator system synchronizes and becomes phase-locked. As shown in [13,32], the phase difference between the motional or actuation signals then provides a highly sensitive, theoretically drift-free measurement of the natural frequency mismatch between the resonators. The theoretical framework of the synchronization of resonators by mutual injection-locking is formalized in [13] in the context of a sensing application. Compared to the mode-localized approach, the mutually injection-locked oscillator (MILO) approach has a theoretically higher sensitivity at the cost of a reduced dynamic range. The resolution of the two approaches is comparable, but the MILO-based approach is intrinsically closed-loop. Furthermore, its output metric, a phase difference, is "quasi-digital" [33]. Hence, we think it may be better-suited to a compact VLSI implementation. A first experimental proof of the drift rejection by a MILO-based sensor is given in [32], showing a good agreement with the theory but limitations due to the fact that both CMOS-MEMS resonators are not on the same chip, and do not endure the same thermal drift. The design of fully co-integrated MILO architecture is outlined in [34], and some simulation results are given. In the present work, the guidelines for the VLSI-compatible design of a fully monolithic co-integrated CMOS-MEMS MILO are given.

3. Design constraints of MILOs

Injection-locking is one way of synchronizing an oscillator to an external frequency reference: a signal from the frequency reference is "injected" into the oscillator, whose frequency may be pulled-in and locked to that of the reference, as first extensively studied by Adler in [15]. In [16], Mirzaei et al. generalized Adler's theoretical results to the case when two LC-tank oscillators are in mutual injection, i.e. each oscillator is the other's frequency reference, with the purpose of generating two stable signals, with a given $\pi/2$ phase difference. It was pointed out that a key issue in the studied architectures was the intrinsic natural frequency mismatch of the LC-tank resonators, due to the fabrication process, resulting in a phase-difference error proportional to (i) the natural frequency mismatch, and (ii) the quality factor Q of the resonators. As proposed in [12], these seeming disadvantages can be turned into assets in the context of a resonant sensing application: a MILO's phase difference "error" (its shift away from a nominal value, e.g. $\pi/2$) can be used as a highly sensitive, intrinsically differential measurement of the natural frequency mismatch of the resonators. The sensitivity of a MILO phase-difference-based sensor is in fact on the order of Q times that of a "conventional" (single oscillator, frequency-based) resonant sensor.

A functional representation of a MILO is shown in Fig. 1, it consists in two nominally-identical MEMS resonators with their