Sensors and Actuators A 220 (2014) 305–315

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Piezoelectric MEMS resonator-based oscillator for density and viscosity sensing

Tomás Manzaneque [a,*], Víctor Ruiz-Díez [a], Jorge Hernando-García [a], Elisabeth Wistrela [b], Martin Kucera [b,c], Ulrich Schmid [b], José Luis Sánchez-Rojas [a]

[a] Microsystems, Actuators and Sensors Group, ETSI Industriales, Universidad de Castilla-La Mancha, 13071 Ciudad Real, Spain
[b] Institute of Sensor and Actuator Systems, Vienna University of Technology, Floragasse 7, 1040 Vienna, Austria
[c] Austrian Center of Competence for Tribology, Viktor-Kaplan-Straße 2, 2700 Wr. Neustadt, Austria

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form
26 September 2014
Accepted 1 October 2014
Available online 13 October 2014

Keywords:
MEMS
Oscillator
Piezoelectric
Liquid
Density
Viscosity

ABSTRACT

The resonant characteristics of a mechanical resonator immersed in liquid provide valuable parameters for density and viscosity sensing. In particular, the combination of microresonators with electronic circuits, for tracking their natural frequency and quality factor, has great interest as low cost and size solution. In this work, we focus on an oscillator featuring an in-liquid piezoelectric microplate resonator as the frequency-selective element. Specifically, by selecting the second-order bending mode in the length-direction, a reliable oscillator operation, for a range of liquid properties, was achieved at moderate frequency. Besides, the out-of-plane vibration allowed for both density and viscosity to be deduced separately. The influence of parasitic capacitances in the device response has been identified as the major difficulty for the realization of the oscillator circuit. To minimize this effect, a compensation method based on a non-released reference device and an instrumentation amplifier was implemented, which resulted in a clear resonance with low baseline and high phase step. In a first test with the resonator immersed in isopropanol, the circuit generated a stable wave with an Allan deviation of $2.32 \cdot 10^{-7}$, improving by one order of magnitude the only published value, to the authors knowledge, for a comparable device in liquid. An alternative tracking system, based on digital phase-locking benchtop instrumentation, was tested with the same resonator, showing a comparable stability ($2.35 \cdot 10^{-7}$) and supporting our approach. Finally, the operation of the system as a sensor was demonstrated. After a calibration process, the density and viscosity of eight test liquids could be compared to measurements with a commercial instrument, showing differences lower than 0.4% in density and 8% in viscosity. The minimum detectable changes were also evaluated, being $4.09 \cdot 10^{-6}$ g/ml for the density and $2.07 \cdot 10^{-3}$ mPa s for the viscosity, both for a viscosity of 7.36 mPa s at 10 samples per second.

1. Introduction

The monitoring of the physical properties of fluids has raised great interest for different industries, such as automotive and food manufacturing. In this context, the determination of the density and the viscosity of liquids, through the measurement of the natural frequency and the quality factor of a mechanical resonator, has already been reported [1–4]. This approach presents several advantages with respect to traditional methods: real-time analysis, on-line configuration, low liquid volumes, etc. The nature of the vibration mode under consideration determines the suitability of the resonator for the mentioned application. For instance, the resonant magnitudes of thickness shear mode (TSM) quartz crystals depend on the product of the liquid density and viscosity, which makes it impossible to solve for them [1]. This problem is inherent to any vibration mode in which the dominant fluid loading is described by the second Stokes problem [5], e.g. in-plane bending [6] or length-extensional [3] modes of thin beams. The fundamental out-of-plane mode of a cantilever is a widely used option to circumvent this limitation, as it presents independent responses to density and viscosity. However, viscous losses may be higher than for in-plane modes, degrading dramatically the quality factor and thus limiting the range of viscosities. It is well-established that higher order out-of-plane modes present better quality factors

* Corresponding author at: Microsystems, Actuators and Sensors Group, Edificio Politécnico, Avda. Camilo José Cela s/n, 13071 Ciudad Real, Spain.
Tel.: +34 926295300x96667.
E-mail address: tomas.manzaneque@uclm.es (T. Manzaneque).

http://dx.doi.org/10.1016/j.sna.2014.10.002

at moderate frequencies [7–9]. In this work we use the second-order out-of-plane mode of a piezoelectrically actuated microplate, looking for a compromise between sensitivity and quality factor.

Focusing on the interface electronics to determine the resonance features, the accurate measurement of the natural frequency, without precision instruments such as impedance or network analysers, can be accomplished by a number of possible circuit configurations based on the resonator. Both open-loop and closed-loop schemes have been reported [10]. Iterative search algorithms are a flexible alternative [11]; aiming for fast and high resolution tracking systems, synchronous-detection, closed-loop systems are well known, either by amplitude peak tracking [12,13] or the widespread phase-locking [14,15]. Regarding oscillator circuits, although they do not offer superior accuracy or resolution with respect to the mentioned phase-locked loops [16], the possibility of eliminating additional off-chip components may reduce the total size, cost and power consumption of the system [17]. This, together with the high simplicity of the final circuit, makes the oscillator a very interesting solution for any potential application scenario.

The oscillator solution, for tracking the natural frequency by means of a frequency counter, has been widely employed in quartz resonators [18–20]. In regard to microdevices, many in-air oscillators can be found in the literature for timing [17] or sensing applications [21–25]. Nonetheless, to the best of the authors' knowledge, only Seo and Brand [23] have reported initial investigations of an oscillator with a microresonator in liquid, based on a disk-shaped structure operated in a rotational in-plane mode. The implementation of an oscillator becomes challenging for MEMS under liquid immersion, as the response is dramatically degraded due to the hydrodynamic loading. Since the resonant signal decreases, it is masked by the electrical parasitic response associated with the actuation/sensing ports of the resonator [26], preventing the fulfilment of the oscillation condition. For this reason, a strategy to cancel the resonator parasitic loads becomes essential. The possible solutions may involve the use of an additional circuit to reproduce the parasitic signal [14,27] or the introduction of a non-released compensating device [28,29], which actually reproduces the structure of the resonator, but having the vibration physically impeded.

Here we present an oscillator that features an Aluminium Nitride (AlN)-actuated microplate, vibrating in an out-of-plane mode while immersed in liquid. The alternative of a silicon monolayer resonator may reduce the damping due to internal material friction [30]. However, when working in liquid media, the overall damping is expected to be dominated by the viscous losses. This, together with the additional complexity that an external actuation mechanism would imply, makes the inclusion of a piezoelectric layer an advantageous choice for actuation in-liquid. The reasonably good value of the admittance peak amplitude (~5 μS), along with the low natural frequency of the chosen mode (~300 kHz), allowed for a great flexibility and simplicity in the design and selection of the electronic parts. Besides, the use of a parasitic cancellation scheme based on a dummy device was found to be crucial. Testing the resonator in isopropanol, a stable periodical signal was achieved, characterized by an Allan deviation of $2.32{\cdot}10^{-7}$ at 292 kHz, between one and two orders of magnitude worse than the in-air MEMS-based oscillators referenced above and improving the value previously reported in liquid [23] of $2.3{\cdot}10^{-6}$. The results with the oscillator circuit are compared to the phase-locked-loop approach, implemented with benchtop instrumentation, taking advantage of advanced and costly signal processing to perform a tracking of the natural frequency. Frequency stabilities in the same order of magnitude were obtained, which shows the advantage of using a simple low-cost oscillator circuit.

In addition, this paper describes the application of the system featuring the resonator and the oscillator circuit for sensing the density and the viscosity of different liquids. By straightforward electrical measurements, the natural frequency and the quality factor were obtained and subsequently correlated to the physical properties of the liquid under test. After a calibration process, the target variables were determined with reasonable accuracy in several liquids with densities and viscosities in the ranges 0.68–0.9 g/ml and 0.39–7.36 mPa s, respectively. The minimum detectable changes were estimated as $4.09{\cdot}10^{-6}$ g/ml and $2.07{\cdot}10^{-3}$ mPa s for the most viscous liquid, representing the worst case.

2. Theoretical background

2.1. Resonator model

Assuming linearity, a single-degree-of-freedom mechanical resonator is described as a damped second-order system [31], with a response of the form:

$$\frac{D(s)}{F(s)} = \frac{\omega_n^2}{k_n\left(s^2 + \frac{\omega_n}{Q}s + \omega_n^2\right)} \quad (1)$$

In (1), D is the displacement, F the applied force, ω_n the natural frequency, k_n the elastic constant, Q the quality factor and s the Laplace variable. For continuous systems with multiple vibration modes, each one can be described by (1), where D and F denote magnitudes distributed over the resonator geometry. This distribution defines the characteristic modal shape, unique for each mode.

Piezoelectric MEMS resonators include a piezoelectric layer for transduction purposes, enabling to convert an applied electric field into a distributed force (actuation mechanism); an electric charge is also generated from the mechanical strain associated with the structure deformation (sensing mechanism). Via the metal electrodes sandwiching the piezo-layer, both the electric field is applied and the electric surface-charges are collected, thus coupling the electrical and mechanical domains. This way, the mechanical resonator can be regarded as an all-electrical system, including it as an element of an electronic circuit. The piezoelectric admittance Y_p is obtained from (1), through the introduction of the actuation (η_a) and sensing (η_s) coupling coefficients [32]:

$$Y_p(s) = \frac{I(s)}{V(s)} = \frac{\omega_n^2\eta_a\eta_s s}{k_n\left(s^2 + \frac{\omega_n}{Q}s + \omega_n^2\right)} \quad (2)$$

In (2), I is the generated current and V the applied voltage. For a complete modelling of the electrical behaviour of real piezoelectric resonators, a parallel capacitance (C_p) that accounts for the dielectric coupling between the electrodes must be considered.

2.2. Oscillator

A resonator-based oscillator consists of a positive-feedback loop circuit as shown in Fig. 1. This system becomes unstable when the Barkhausen criterion is met, i.e. the loop gain reaches a modulus equal or greater than 1 and its phase equals 0°. The resonator is the frequency-selective element, as its piezoelectric (motional) admittance Y_p performs 0° at the natural frequency (ω_n). The gain A is introduced to compensate the lack of loop gain to meet the criterion at that frequency.

The performance of an oscillator, regarded as the frequency stability of the output wave, may be given by the response of the system to small phase perturbations. To model this, the system is assumed to be oscillating at a stationary frequency, while random phase variations are considered. In this phase-noise domain, the