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Piezoelectric resonant sensors with contactless interrogation for mass-sensitive and acoustic-load detection[☆]

M. Ferrari*, M. Baù, E. Tonoli, V. Ferrari

Department of Information Engineering, University of Brescia, Via Branze 38, 25123 Brescia, Italy

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ABSTRACT

Piezoelectric resonator sensors that can be contactless interrogated as passive elements are proposed. The interrogation technique is based on time-gated excitation and detection phases, exploiting the sensing of the transient response of the resonator to derive both its fundamental resonant frequency and quality factor. The technique provides the advantage to be to first order independent on the interrogation distance across the operating range. The proposed system can be exploited for the measurement of physical or chemical quantities affecting the electromechanical resonant response of the sensor. In particular, PZT thick-film resonators with fundamental resonant frequencies of 5.7 MHz and 6.5 MHz have been successfully interrogated both in air and in liquid environments. Operating distances of up to 20 mm in air have been attained. The principle has been applied implementing a variable-mass resonator sensor for humidity sensing in closed volumes and a submersible resonator sensor operated in liquid environments.

1. Introduction

The contactless interrogation of passive sensors can be exploited in applications where cabled solutions are not allowed and environmental conditions are demanding. The resonant sensing principle represents a robust approach in contactless operation since it can minimize the detrimental influence of the interrogation distance on the readout signal. In this perspective, piezoelectric resonators are suitable to be used as contactless passive resonant sensors for the measurement of quantities affecting their resonant response [1–3].

Quartz crystal resonators (QCR) are commonly employed as quartz crystal microbalance (QCM) mass sensors in many biochemical applications [4] and contactless interrogation techniques have been reported for QCRs. For instance, a QCM immunosensor is proposed in [5], which exploits the radiation of the quasistatic electric field to excite the 13th overtone shear resonant frequency of special electrodeless crystals. As an alternative, a technique for contactless readout of ordinary AT-cut quartz crystal resonator sensors is reported in [6].

As an alternative to QCRs, resonant piezo-layer (RPL) sensors, made of piezoelectric ceramic films fabricated in thick-film technology on alumina, have been demonstrated as acoustic-wave gravimetric sensors [7,8]. In contrast to homogeneous resonators, such as QCR sensors, RPL devices are composite resonators, comprising a piezoelectric layer acoustically coupled to a nonpiezoelectric substrate. The contactless interrogation of thick-film RPL sensors is innovatively addressed in the present paper.

Contactless excitation and detection of mechanical resonances of resonator sensors can be performed either in the frequency or time domains [9–11]. Frequency-domain techniques typically rely on simultaneous excitation and detection phases and an effective reflected impedance or a transfer function has to be measured. However, these techniques can pose significant challenges to ensure adequate dynamics and signal-to-noise ratio.

As an alternative, in this work a time-gated contactless interrogation technique for RPL sensors is proposed and experimentally validated. The technique excites the sensor for a finite time duration and then detects the decaying resonant response extracting both the resonant frequency and quality factor.

The system description, equivalent model and experimental results on applications of the proposed method and sensors are reported in Sections 2–4 respectively.

2. System description

2.1. Sensor structure

Piezoelectric resonant sensors have been fabricated by means of screen-printing technology adopting alumina as the substrate. As

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* Corresponding author. Tel.: +39 030 3715899; fax: +39 030 380014.
E-mail address: marco.ferrari@ing.unibs.it (M. Ferrari).

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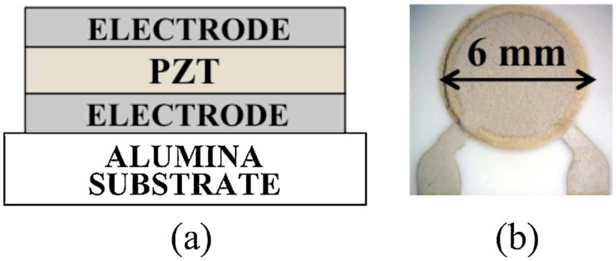

Fig. 1. (a) RPL structure and (b) picture of the fabricated device.

shown in Fig. 1(a), the sensor has a sandwich structure composed of bottom and top electrodes, printed from a PdAg ink (Heraeus C1214D), with an interposed piezoelectric film made by printing multiple layers of a lead zirconate titanate (PZT) paste. The piezoelectric paste was prepared by mixing a PZT powder (Ferroperm PZ26) with 20 wt.% of PbO and adding a solution of ethylcellulose in terpineol as the liquid vehicle. The whole process consists of multiple screen-printing/drying/firing cycles [7]. After firing, the PZT layer has been poled along its thickness at about 4 MV/m at 150 °C for 30 min. In the resulting structure, the PZT film is acoustically coupled to the substrate, leading to a composite resonator named resonant piezo-layer (RPL) sensor. Due to the poling direction along the film thickness, the RPL sensor driven by an AC voltage at the electrodes sustains longitudinal acoustic waves thereby working in thickness expansion, as opposed for instance to AT-cut QCR sensors based on shear waves. RPL resonators can be used as bulk acoustic-wave sensors responsive to an acoustic surface load [7,8].

Typical dimensions are 6 mm for the electrode diameter, 250, 10 and 90 μm for the thickness of the substrate, electrode and PZT layers respectively. This results in a fundamental resonant frequency f_m of around 6–7 MHz, while higher values can be achieved for thinner devices. Fig. 1(b) shows an example of fabricated RPL sensor, whose impedance spectrum, measured with a HP4194A impedance analyser around the sensor fundamental thickness-expansion resonance, is shown in Fig. 2.

2.2. Proposed interrogation principle

The interrogation technique is based on a gated operation, exploiting the separation in time between excitation and detection phases, somewhat similarly to what was previously proposed for silicon micromechanical resonators [12]. In the present case, however, the electromechanical interaction in the resonator sensor is piezoelectric instead of magnetodynamic, therefore no magnets are required.

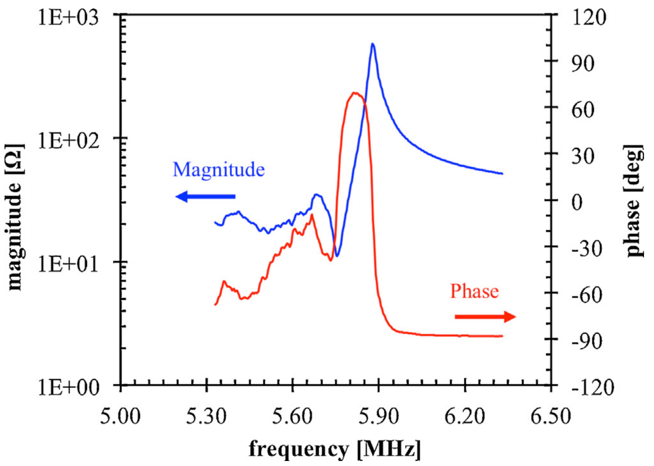

Fig. 2. Measured impedance spectrum of a RPL sensor around its fundamental thickness-expansion resonance.

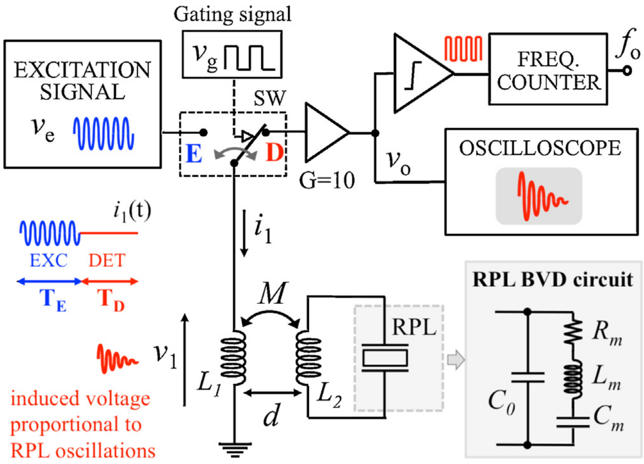

Fig. 3. Simplified block diagram of the time-gated contactless interrogation system.

As shown in Fig. 3, a primary coil L_1 is electromagnetically air-coupled to a secondary coil L_2 connected to the electrodes of the RPL sensor. During the excitation phase a gating signal v_g sets the switch *SW* to the position *E*, connecting for a time interval T_E the primary coil L_1 to the excitation signal v_e which results in a gated sinusoid at frequency f_e. By exploiting the electromagnetic air-coupling between the two coils, the excitation signal is transmitted to the RPL sensor which is excited around its fundamental thickness resonance. Since the principle of operation relies on the detection of the RPL transient response, the excitation condition of $f_e = f_m$ is not strictly required to excite the resonator, which is advantageous since the mechanical resonant frequency might not be exactly known in advance. Nevertheless, when the condition is satisfied, the effectiveness of the excitation is increased.

In the detection phase the gating signal v_g sets the switch *SW* to the position *D* for a time interval T_D disconnecting the excitation from the primary coil, and thus also from the RPL sensor, and connecting the primary coil to the readout circuit. In this condition the piezoelectric resonator undergoes decaying oscillations at frequency f_{dm}, whose initial amplitude is inversely related to the difference between the excitation frequency f_e and the fundamental thickness-expansion resonance of the RPL. The mechanical vibrations of the piezoelectric resonator force a current in the coil L_2 and consequently an induced readout voltage v_1 can be sensed across L_1. The induced voltage v_1 is further amplified by means of a high-impedance voltage amplifier stage of gain $G = 10$ and then, by means of a zero-crossing detector, converted into a square waveform with frequency $f_0 = f_{dm}$, which can be measured with a frequency counter.

3. Equivalent model

Piezoelectric electroacoustic devices can be modelled adopting the Mason's distributed-parameter electromechanical circuit [2,13]. Assuming to operate around one of the resonant modes of the piezoelectric resonator, the Mason's model can be approximated by the Butterworth–van Dyke (BVD) equivalent lumped-element circuit. The BVD circuit is composed of a motional, i.e. mechanical, branch and an electrical branch formed by the parallel capacitance C_0. The motional branch comprises the series inductance L_m, capacitance C_m and resistance R_m, which respectively represent the equivalent mass, compliance and energy losses of the RPL sensor. With respect to the BVD circuit, the series