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Piezoelectric Resonant Sensors with Contactless Interrogation for Mass-Sensitive and Acoustic-Load Detection

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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. The proposed system can be exploited for the measurement of physical or chemical quantities affecting the electromechanical resonant response. In particular, experimental results show the successful interrogation of variable-mass resonator sensors for humidity sensing in closed volumes and submersible resonator sensors operated in liquid environments.

Keywords: Piezoelectric sensor; Contactless interrogation; Resonant sensor; Time-gated technique; Mass sensing; Acoustic load

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 minimizes 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. Quartz crystal resonators (QCR) and resonant piezo-layers (RPL) [1] are commonly employed as mass sensors in many bio-chemical applications [2] and contactless interrogation techniques have been reported for QCRs [3], though they typically require bare crystals or special-electrode sensors. We propose a time-gated contactless interrogation technique and validate it on RPL sensors.

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2. Sensor structure and interrogation principle

As shown in Fig. 1(a), the structure of the proposed RPL sensor is made of a lead zirconate titanate (PZT) layer, sandwiched between two electrode layers, screen-printed on alumina substrate. The PZT layer is poled along the thickness, Fig. 1(b) shows a RPL sensor, whose impedance spectrum, measured with a HP4194A impedance analyser around the fundamental resonance, is shown in Fig. 1(c).

The interrogation technique is based on a gated operation, somewhat similarly to what was previously proposed for silicon micromechanical resonators [4]. In this case, however, no additional magnets are required. As shown in Fig. 2, a primary coil L_1 is electromagnetically air-coupled to a secondary coil L_2 connected to the electrodes of the RPL. During the excitation phase the signal v_e excites the RPL about its fundamental thickness-expansion resonance, while in the detection phase the excitation signal v_e is turned off and the resonator undergoes decaying oscillations at frequency f_{dm}, which can be contactless sensed by measuring the voltage v_1 induced back across L_1. The voltage v_1 is then amplified and converted into a square waveform with frequency $f_o=f_{dm}$, which can be measured by a frequency counter.

The system has been modelled assuming a lumped-element approach, with the RPL modelled around its fundamental thickness-expansion resonance by adopting the Butterworth-van Dyke (BVD) circuit shown in Fig. 2. Accordingly, the induced voltage v_1 during the detection phase can be expressed as an exponentially damped sinusoid at frequency f_{dm}, which represents the RPL mechanical response. The mutual inductance M, which strongly depends on the interrogation distance d, virtually does not affect the RPL response parameters, thus making the principle robust against the interrogation distance.
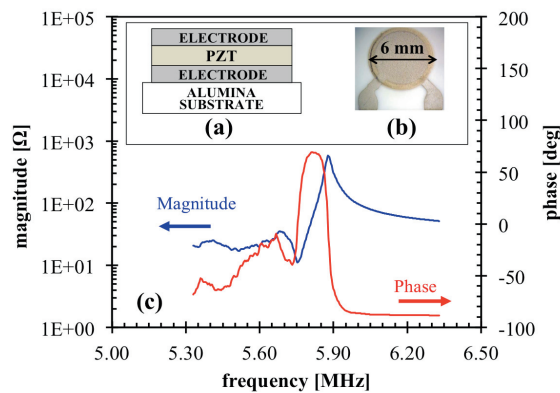

Fig. 1. (a) RPL structure, (b) picture of the manufactured device, and (c) measured impedance spectrum.
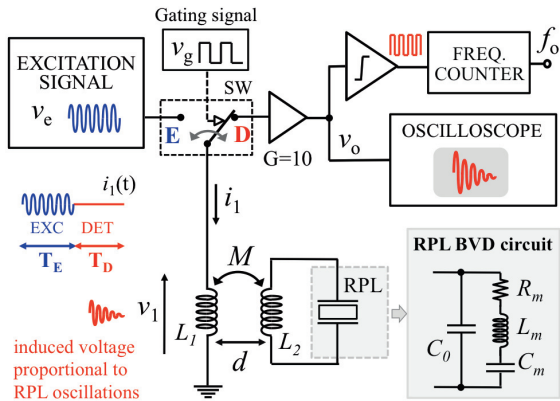
Fig. 2. Simplified diagram of the time-gated contactless interrogation system.

3. Experimental results

The principle has been applied to a 5.7 MHz RPL sensor. The RPL BVD parameters are: C_0=370 pF, R_m=9.83 Ω, L_m=48.09 µH and C_m=16.24 pF. Fig. 3 shows the typical readout voltage v_o measured during the detection phase, with interrogation distance d=15 mm and $L_1=L_2$=8.5 µH. The frequency f_e and amplitude of the excitation signal v_e have been set to 5.9 MHz and 5 V, respectively. As predicted by the theoretical model, the RPL mechanically responds with a damped sinusoidal signal. From the envelope a damped resonant frequency $f_o=f_{dm}$=5.893 MHz and a quality factor Q=160 can be estimated. These values are in good agreement with the predictions of the model, which are f_{dm}=5.856 MHz and Q=174.

Fig. 4 shows the readout frequency f_o and signal amplitude v_o versus the interrogation distance d. Typical values for d are in the order of 2 cm and, as predicted by the model, it does not affect the measured readout frequency, acting only as scaling factor on the amplitude of the readout voltage.
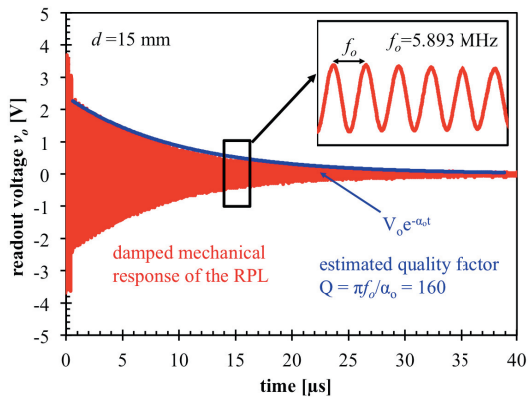
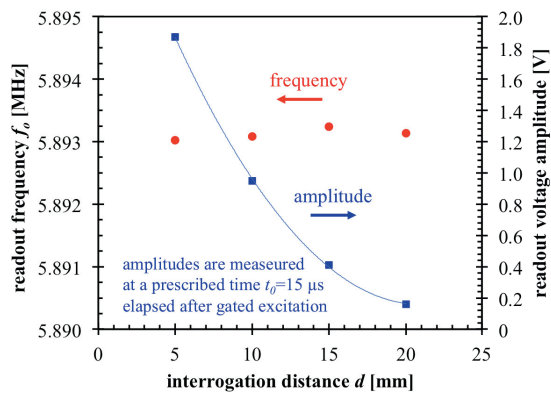Fig. 3. Response of a 5.7 MHz RPL during the detection phase.

Fig. 4. Measured readout frequency f_o and readout voltage amplitude for different values of the interrogation distance d.

The interrogation principle has been used to perform contactless gravimetric humidity measurements using a 6.5 MHz RPL coated with Polyvinylpyrrolidone (PVP) as sensing film. The BVD parameters of the coated resonator at room atmosphere are: C_0=1.02 nF, R_m=9.95 Ω, L_m=5.94 µH and C_m=104.64 pF. The block diagram of the measurement setup is shown in Fig. 5 [5]. The RPL sensor, connected to the secondary coil, has been placed inside a stainless steel chamber with a Teflon bottom side. The relative humidity (RH) inside the chamber has been varied with a computer-driven system and monitored by a RH sensor (Gefran S6000) used as a reference. The measurements have been performed with a temperature inside the sensor chamber of 26°C±0.5°C, with the interrogation distance d=2 cm and L_1=L_2=8.5 µH. Fig. 6 shows the measured response of the RPL sensor versus time, compared with the RH inside the sensor chamber. The measured frequency shift Δf_o follows the RH trend, thus demonstrating the capability of the developed system to contactless interrogate the sensor from outside the chamber.
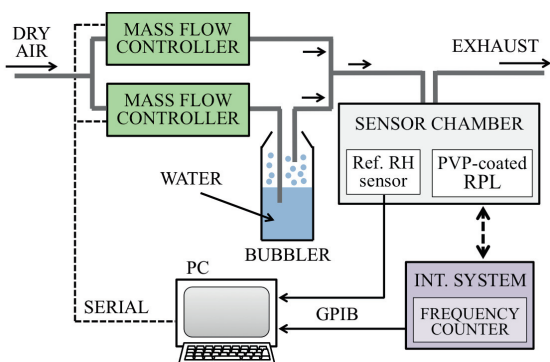
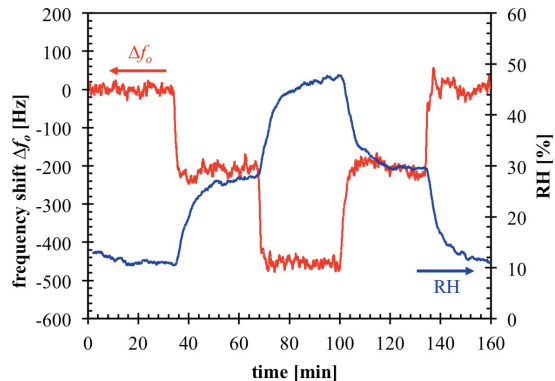Fig. 5. Block diagram of the humidity measurement system.

Fig. 6. Contactless RH measurements with a PVP-coated RPL.

The 5.7 MHz RPL and the secondary coil L_2=3.2 µH have been arranged together composing a sealed submersible sensor capsule, as shown in Fig. 7, which has been used to perform contactless interrogation

with the sensor operated in liquid environments. Fig. 8 shows the response of the RPL sensor operated in water and ethanol. In the liquid-filled cell with horizontally mounted RPL, the air/liquid interface acts as a reflection surface for the compressional waves produces by the RPL, generating a standing wave pattern. The liquid evaporation results in periodic changes in the readout frequency f_o. The periodicities are $T_w = \lambda_w/2k_w$ in water and $T_e = \lambda_e/2k_e$ in ethanol, with k_w and k_e representing the liquid evaporation rates expressed in m/s, and λ_w and λ_e representing the wavelength of the compressional wave in the two liquids.
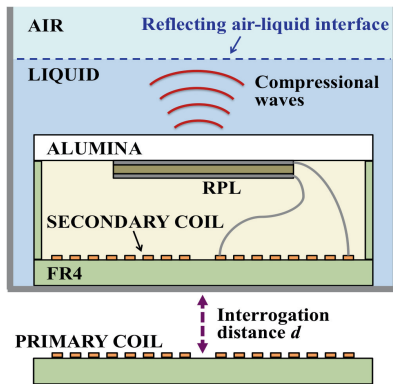

Fig. 7. Apparatus used for the 5.7 MHz RPL submersible sensor capsule operated in liquid environments.
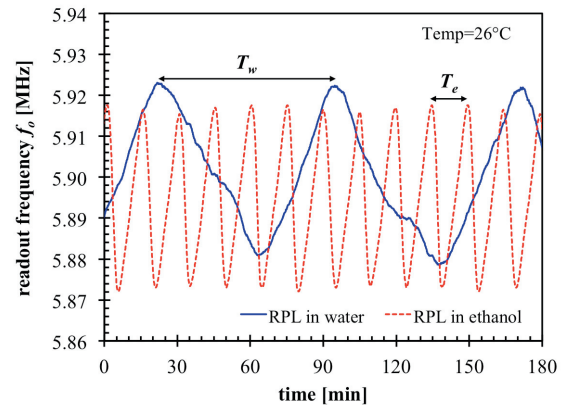

Fig. 8. Measured response of the RPL sensor operated in water and ethanol.

4. Conclusions

Piezoelectric resonator sensors based on PZT thick films that can be contactless interrogated as passive elements have been proposed. The developed interrogation technique is based on the time separation of the excitation and detection phases, exploiting the sensing of the resonator transient response. The principle has been studied by means of a lumped-element equivalent circuit. Experimental results validate the theoretical model and show the successful contactless interrogation of the proposed sensors for humidity sensing in closed volumes and in a submersible sensor capsule operated in liquid. The interrogation technique is exploitable for chemico-physical measurements of quantities affecting the sensor resonant response.

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