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Contactless Electromagnetic Switched Interrogation of Micromechanical Cantilever Resonators

Marco Baù*, Vittorio Ferrari, Daniele Marioli, Emanuele Tonoli

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

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Abstract

A principle for contactless interrogation of passive micromechanical resonator sensors is proposed, in which an external primary coil is electromagnetically air-coupled to a secondary coil connected to a conductive path on the resonator. The interrogation periodically switches between interleaved excitation and detection phases. During the excitation phase the resonator is driven into vibrations, while in the detection phase the excitation signal is turned off and the decaying oscillations are contactless sensed. The principle advantageously avoids magnetic properties required to the resonator, thereby ensuring compatibility with standard microfabrication processes. Results are reported on the successful implementation on a MEMS SOI microcantilever resonator working as a mass sensor for which the deposition and evaporation of a water droplet have been detected.

Keywords: Contactless sensor; MEMS microcantilever;

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1. Introduction

Recently, sensors contactless interrogated by an external unit have been extensively investigated. The lack of a physical contact is attractive for operations where cabled solutions are not allowed, such as measurements in inaccessible environments or in closed packages. Battery-powered contactless sensors, which are currently the most adopted solution, present the significant drawback of requiring periodical recharge/replacement of the sensor battery. Alternatively, the sensing system can be battery-less and powered by either exploiting the energy transfer from the external reader or the energy-harvesting from the environment. At the same time, the availability of entirely passive sensing elements that can be contactless interrogated without the need of active circuitry on board would be attractive for a variety of applications involving hostile environments that can be incompatible with active electronics, such as high-temperature environments. In this perspective, the exploitation of the resonant measurement principle represents a robust approach for contactless operations involving entirely passive structures used as basic sensing elements for a wide variety of measurands.

Usually, contactless electromagnetic interrogation is obtained through impedance measurements on an external coil in

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* Corresponding author. Tel.: +39-030-3715896; fax: +39-030-380014.
E-mail address: marco.bau@ing.unibs.it.

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proximity of the resonator [1] or by exploiting an additional probing magnetic field [2]. In both cases, the excitation and detection processes are simultaneous, which poses significant challenges to ensure adequate dynamics and signal-to-noise ratio. As an alternative, this work proposes a novel approach that separates in time the excitation and detection phases and exploits the transient response of a MEMS microcantilever, adopted as resonator. The principle can be applied to measurement of quantities affecting either the resonant frequency or/and the quality factor of the resonator [3].

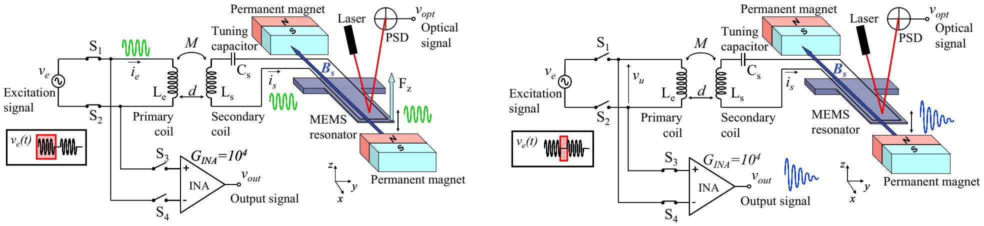
2. Operating principle

Fig. 1 illustrates the operating principle that employs two interleaved phases made by gated excitation followed by detection of decaying mechanical oscillations of the MEMS resonator. The coil L_e is located at distance d from the coil L_s which is connected to a conductive path on the microcantilever resonator. To enhance both the excitation and detection phases, a series capacitor C_s is added to tune the L_s-C_s electrical resonance to the mechanical resonant frequency of the microcantilever. In the excitation phase, shown in Fig. 1a, a gated sinusoid at frequency f_e is applied and the current i_s induced in the on-chip path interacts with the static magnetic field B_s. A Lorentz force $F_z=B_s i_s w$, where w is the width of the microcantilever, is generated which acts on the microcantilever and sets it into vibration.

In the detection phase, shown in Fig. 1b, the excitation signal is switched off and the microcantilever undergoes decaying oscillations with an initial amplitude inversely related to $|f_e - f_r|$ and with its damped mechanical resonant frequency $f_d = f_r(1-1/4Q^2)^{1/2}$, where f_r is the undamped mechanical resonant frequency. In particular $f_d \approx f_r$ for high values of the quality factor Q of the resonator. Due to the magnetic field B_s an induced voltage is generated which forces a current in L_s and in turn a voltage v_u across L_e. The voltage v_u is composed of two terms, the first is related to the electrical ringing generated by the contributions of the switch commutations and the series resonance of L_s-C_s, whilst the second term is due to the decaying mechanical response of the resonator. The analytical expression for the signal v_u can be written as:

$$v_u(t) = V_s e^{-\alpha_s t}\cos(2\pi f_{ds} t - \theta_s) + V_m e^{-\alpha_m t}\cos(2\pi f_{dm} t - \theta_m) \tag{1}$$

where V_s, α_s, f_{ds} and θ_s are respectively the voltage amplitude, the exponential attenuation rate, the damped resonant frequency and the phase of the electrical ringing, while V_m, α_m, f_{dm} and θ_m are respectively the voltage amplitude, exponential attenuation rate, the damped resonant frequency and the phase related to the mechanical vibrations. The voltage v_u is further amplified to obtain the output voltage v_{out}.



(a) *(b)*

Fig. 1. Schematic diagram of the interrogation system: (a) excitation phase; (b) detection phase.

3. Experimental setup and results

The principle has been implemented according to Fig. 1. A value of about 67 mT for the static magnetic field B_s generated by the two magnets has been measured in proximity of the resonator by means of a linear Hall effect sensor (Melexis MLX90242ESE-BC03). The primary and secondary coils have an inductance of L_e=1 mH and L_s=5 mH respectively, measured at a frequency of 10 kHz, while the tuning capacitance is C_s=47 nF. The adopted resonator has been fabricated in a BESOI (Bulk and Etch-back Silicon On Insulator) technology offered by the CNM (Centro Nacional de Microelectronica) of Barcelona [4]. Fig. 2 shows a schematic diagram of the layers of the microfabrication process and a picture of the microcantilever resonator of dimensions 1500 x 700 x 15 µm. The on-chip conductive path running along the edges of the microcantilever is also visible.

Preliminarily, the MEMS resonator has been characterized by means of a previously developed single point triangulation system [5]. Fig. 3 shows the frequency response of the amplitude vibration when an excitation current is forced in the conductive path of the microcantilever located in the static magnetic field B_s. The resonant frequency is about f_r=10186 Hz and the quality factor is $Q=f_r/\Delta f$=424, where Δf is the frequency range where the amplitude is at $2^{-1/2}$ with respect to the amplitude at f_r.

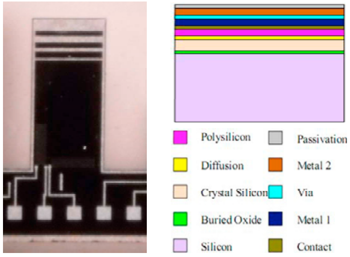


Fig. 2. Picture of the microcantilever (1500 x 700 x 15 µm) and schematic diagram of the process layers of the BESOI technology.

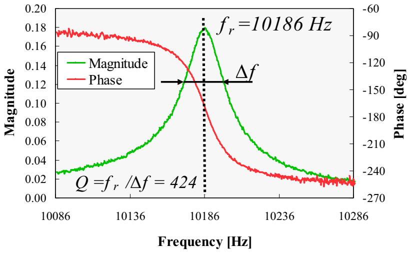


Fig. 3. Frequency characterization of the resonator obtained with an optical system.

Fig. 4 reports a typical readout signal measured at a distance d=2 mm between the two coils when a sinusoidal excitation signal of peak amplitude of 6.1 V has been applied for 35 ms at the frequency $f_e=f_r$. As expected from (1), after an electrical ringing, the decaying mechanical response of the resonator can be sensed. From the envelope of the decaying response and the damped resonant frequency, an estimation of the quality factor Q of about 432 can be derived which is in good agreement with the optical response of Fig. 3 and confirms that, for high values of Q, $f_d \approx f_r$.

In Fig. 5 the amplitudes of the readout signals v_{out} and v_{opt}, from the contactless interrogation and optical systems respectively, at a prescribed time t_0 after gated excitation are measured as a function of the distance d for a peak excitation voltage of 6.1 V applied for 35 ms at resonant frequency f_r=10186 Hz. The experimental results demonstrate that the principle is effective over a working distance d up to 1 cm.

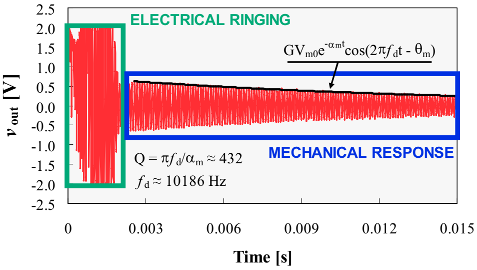


Fig. 4. Output signal v_{out} of the interrogation system measured during the detection phase.

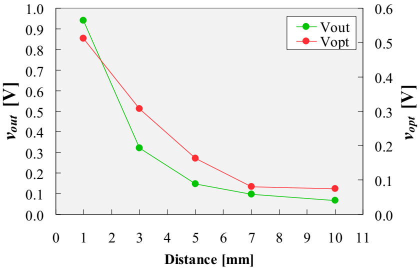
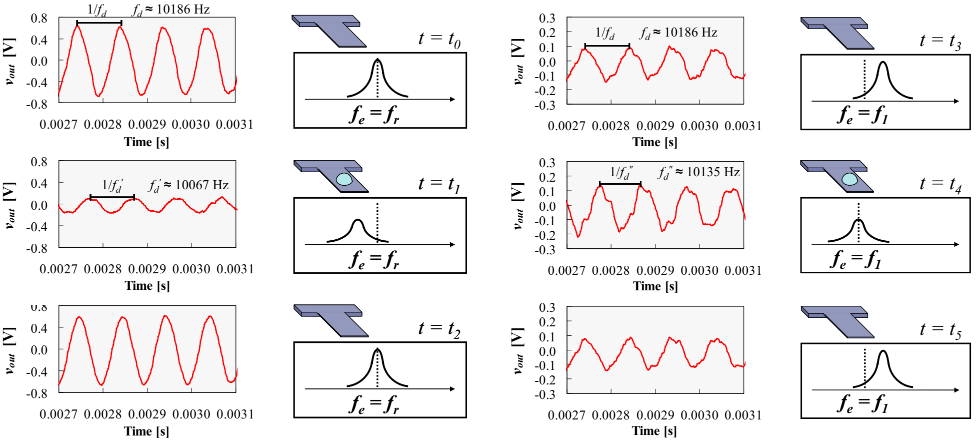


Fig. 5. Readout signals v_{out} and v_{opt} for different values of distance d between the two coils L_e and L_s.

The principle has been successfully validated by measuring the response due to mass loading caused by an evaporating water droplet deposited on the microcantilever. In Fig. 6a the resonator is excited with a signal at resonant frequency $f_e=f_r$=10186 Hz. At $t=t_0$ the output signal v_{out} is measured with the microcantilever in its unloaded state, corresponding to a decaying oscillation at frequency f_d. At $t=t_1$ a drop of water deposited on the microcantilever causes the frequency of the decaying oscillation to decrease to $f_d'<f_d$. Consequently, the vibration amplitude decreases according to the difference between f_d' and the excitation frequency f_e and the quality factor Q is also affected. At $t=t_2$,

when water has evaporated the resonator returns to its unloaded state. Conversely, in Fig. 6b the microcantilever is initially excited out of resonance at frequency $f_e = f_1 = 10120$ Hz. At $t=t_3$ the output signal v_{out} is measured with the resonator in its unloaded state corresponding to a decaying oscillation at f_d. At $t=t_4$ a drop of water is deposited on the microcantilever shifting the damped resonant frequency at the value $f_d'' < f_d$. The vibration amplitude in this case increases as f_d'' approaches the excitation frequency $f_e = f_1$. At $t=t_5$, when the water droplet has evaporated the resonator returns to its unloaded state.



(a) *(b)*

Fig. 6. Responses due to the mass load caused by an evaporating water droplet deposited on the microcantilever excited with (a) a signal of frequency $f_e = f_r = 10186$ Hz; (b) a signal of frequency $f_e = f_1 = 10120$ Hz.

4. Conclusions

In the present work a novel system for the contactless electromagnetic interrogation of entirely passive microresonators has been proposed. The developed technique is based on the separation in time of excitation and detection phases, exploiting the transient response of the resonator and allowing for detection of changes in both the damped resonant frequency and the quality factor of the resonator. The principle has been implemented and tested on a MEMS SOI microcantilever resonator. Experimental results have successfully demonstrated the principle and shown a working distance of up to 1 cm in the tested conditions. The proposed system can be exploited for the measurement of physical or chemical quantities affecting either the resonant frequency or/and quality factor of the microresonator.

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