Acoustic transducers as passive sensors probed through a wireless radiofrequency link

Nicolas Chrétien [1], **Jean-Michel Friedt** [1], **Gilles Martin** [2], **Sylvain Ballandras** [3]

1. *SENSeOR SAS, c/o FEMTO-ST Time & Frequency,*
32 avenue de l'Observatoire, 25044 Besançon, France
{nicolas.chretien,jmfriedt}@femto-st.fr

2. *FEMTO-ST Time & Frequency,*
32 avenue de l'Observatoire, 25044 Besançon, France
gilles.martin@femto-st.fr

3. *Frec|n|sys SAS,*
TEMIS Innovation, 18 Rue Alain Savary, 25000 Besançon
sylvain.ballandras@frecnsys.fr

ABSTRACT. *The increasing demand for wireless monitoring of physical parameters has generated a substantial effort in the development of various systems based either on active or passive sensors, depending on the environment to which the sensing part is submitted. Passive devices are particularly attractive when dealing with harsh environment, preventing the use of any junction-based electronics. In this work, acoustic transducers are used as passive battery-less sensors interrogated through a wireless radiofrequency link. These sensors are exploiting the sensitivity of the waves generated by the transducer to physical parameters – temperature, i stress, pressure. Physical parameter changes are affecting the medium supporting the waves, thus yielding phase velocity shifts due to non-linear thermoelastic properties of the substrate material. These shifts can be detected by monitoring the resonance frequency or phase conditions of the corresponding devices (respectively resonators and delay lines). In this document, we describe basic demonstrations of the various wireless probing schemes matching the acoustic sensor spectral characteristics. We demonstrate wireless probing of the frequency or phase shifts both in resonator (narrowband) or delay line (broad band) configurations and emphasize the advantage and drawback of each configuration.*

RÉSUMÉ. *La demande soutenue de mesure à distance de grandeurs physiques a engendré de notables efforts pour la mise au point de différents systèmes fondés aussi bien sur des capteurs actifs ou passifs suivant les conditions opératoires auxquelles lesdits systèmes sont soumis. Les dispositifs passifs sont particulièrement intéressants lorsque confrontés à des environnements* *sévères peu compatibles avec l'utilisation de composants microélectroniques intégrant des jonctions. Dans la présente étude, des transducteurs à ondes élastiques sont exploités comme capteurs passifs (sans énergie embarquée) interrogeables par une liaison sans fil radiofréquence. Ces capteurs sont fondés sur la sensibilité des ondes engendrées par ledit transducteur aux paramètres physiques tels que la température, les contraintes ou effet de pression. Les variations paramétriques correspondantes modifient les propriétés mécaniques du substrat piézoélectrique monocristallin au sein duquel les ondes se propagent, induisant en premier lieu des variations de vitesse de phase. Celles-ci se traduisent par des dérives en fréquence ou des conditions de phase de résonateurs et lignes à retard, respectivement. Nous présentons dans ce document des expériences pédagogiques pour se familiariser avec les diverses stratégies d'interrogation des capteurs respectant les caractéristiques spectrales des diverses configurations. Ainsi, nous montrons comment mesurer lesdites variations paramétriques en suivant par interrogation sans fil la fréquence de résonance ou les échos définis temporellement de dispositif à bande étroite (résonateur) ou à bande large (ligne à retard) en insistant sur les avantages et inconvénients de chaque approche.*

KEYWORDS: *acoustic wave transducer, passive, sensor, wireless, radiofrequency, RADAR*

MOTS-CLÉS : *transducteur à ondes élastiques, passif, capteur, sans-fil, radiofréquence, RADAR*

DOI:10.3166/I2M.13.3-4.159-178

1. Introduction

The increasing demand for wireless monitoring of physical parameters for numerous applications such as health monitoring of machineries or industrial process optimization has yield the development of various systems based either on active or passive sensors. Harsh environment conditions have more specifically received a strong attention the passed years, taking advantage of materials capable to withstand temperature in excess of 500^{o}C exhibiting properties robust enough to guaranty the sensor operation on the whole operation range. In particular, acoustic transducers have been revealed well suited for wireless sensing applications. Mainly based on piezoelectric excitation/detection principles, these devices have been combined with materials such as Langasite or Aluminum Nitride to address extended temperature range monitoring (up to 700^{o}C) successfully. They can exploit either bulk acoustic wave (BAW) or surface acoustic waves (SAW), the latter being particularly considered because of its adequation with radiofrequency (RF) interrogation protocols and standards and its maturity. Among the very interest of these SAW devices, their collective fabrication (inducing reasonably low costs) and their compactness are of primary importance for most of the concerned applications. Moreover, as for all passive devices, no on-board energy is needed since the interrogation unit – operating following principles based on RADAR systems – generates the electromagnetic pulse needed to probe the sensor response. The RADAR receiver identifies a given quantity – either resonance frequency or time of flight relative to the device operation principle and representative of the physical quantity under investigation. The sensor design challenge lies in identifying the appropriate piezoelectric substrate orientation maximizing the phase velocity variation or resonance condition changes when the physical quantity under investigation is varied. On the other hand, an effort must be paid to minimize or suppress parametric cross-talks by using appropriate sensor architecture, differential structures being preferred as much as possible. Also a special care must be dedicated to the basic properties of the device, namely the electro-mechanical coupling coefficient and/or the quality factor of the resonance to efficiently convert electromagnetic energy to mechanical energy and vice-versa, and therefore guaranty the sen sor operation on the whole operating range. Generally, the sensing principle of these devices is based on phase velocity variations of a mechanical wave as well as the modification of the waveguide dimensions and parametyers affected by external quantities such as temperature (Bao *et al.*, 1987; Buff *et al.*, 1998; Bruckner *et al.*, 2003), stress (Pohl *et al.*, 1999), or mass loading (Dong *et al.*, 2001; Wang *et al.*, 2009) for chemical compound detection. An accurate modelling step is mandatory to design a sensor which does not simply act as a transducer sensitive to all external effects but solely to the quantity under investigation.

Applications of passive sensors based on acoustic transducers include preventive maintenance on rotating or vibrating structures in which a wired connection between the sensor and the data logging instrumentation is not possible and no maintenance of the sensor is possible (*e.g* battery replacement in an active wireless device configuration), buried sensors which are no longer accessible once installed (Friedt *et al.*, 2011; 2013), or temperature ranges (Bruckner *et al.*, 2003; Cunha *et al.*, 2008) inaccessible to silicon based CMOS technology as used in radiofrequency identification (RFID) tags.

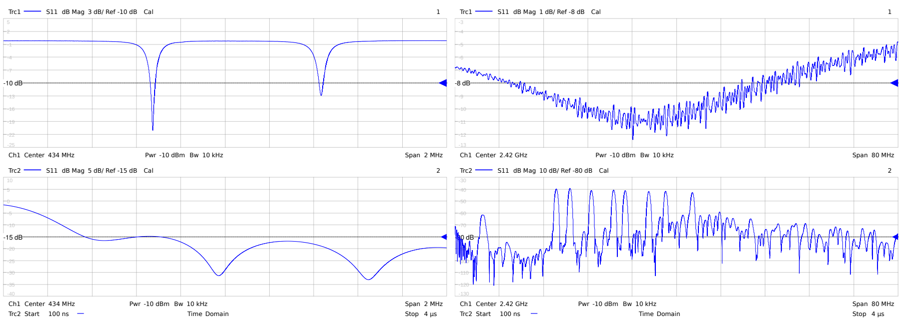

Figure 1. Two basic acoustic sensor designs: the narrowband resonator (left) and the wideband acoustic delay line used as temperature sensor by CTR (right). Top is the frequency domain response, bottom is the time domain

Two broad geometries of sensors have been considered (Figure 1) The narrowband resonator is based on the acoustic wave energy storage in a cavity defined by Bragg mirrors surrounding interdigitated transducers connected to an antenna. The wave travels in the cavity Q times, with Q the quality factor of the resonator, and thus interacts with a combination of the acoustic properties of the bare piezoelectric material and the patterned electrodes, hence requiring minute resolution on the electrode metallic thickness and geometry to coherently accumulate energy in the cavity. Figure 1 (left) exhibits the reflection coefficient of a dual-resonator configuration transducer used as a differential temperature sensor by SENSeOR. Another approach consists in launching a mechanical wave on a bare single-crystal piezoelectric substate using the inverse piezoelectric substrate by generating an electrical field with broad-band interdigitated transducers patterned on a single-crystal piezoelectric substrate. This pules propagates at a velocity dependent on the environmental conditions of the sensor (temperature, stress) before being reflected by mirrors consisting of patterned electrodes. The acoustic impedance mistmatch between the free space velocity and the electrode-coated areas of the sensor means that a fraction of the incoming acoustic wave is reflected back to the interdigitated transducer electrodes, hence generating an electromagnetic pulse through the direct piezoelectric effect. This latter approach is named the acoustic delay line configuration. While the resonator complies with the low-bandwidth low-frequency (434 MHz) ISM band allowing for high penetration depths of the electromagnetic wave in dielectric media, the information content is reduced to a resonance frequency and possibly a resonance bandwidth. On the other hand, the high-frequency (2450 MHz) delay line allows for reduced antenna dimensions and improved interrogation strategies thanks to the large information content as visible with the multiple features of the frequency-domain spectrum.

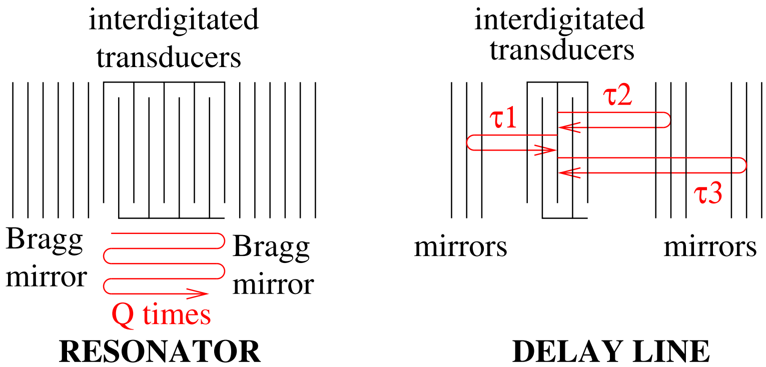

Figure 2. The two architectures considered in this document include the basic acoustic transducer geometries of the resonator (left) and the delay line (right). Red arrows indicate the acoustic wave propagation path between the electrodes shown as black lines

The choice of the piezoelectric substrate depends on the application and on the propagation principle: highly coupled lithium niobate or lithium tantalate for SAW delay lines (Figure 2, right) requiring wide frequency band operating conditions (the excitation of the device is spread on the whole accessible frequency band) and quartz or other weakly coupled materials (langasite, gallium orthophosphate, AlN/silicon, etc) for narrow band interrogation using SAW or BAW resonators (Figure 2, left). The resonator is designed with interdigitated transducers (IDT) surrounded by mirrors for confining the acoustic wave energy in the cavity by reflecting the wave Q times, with Q the resonator quality factor. The IDT act as electrodes for converting the incoming electromagnetic wave to a mechanical wave, most sensitive to the environmental effect on the piezoelectric substrate mechanical properties and hence acoustic velocity. The delay line geometry requires a narrower set of IDTs for launching a widebande acoustic pulse reflected by mirrors patterned on the substrate and acting as reflectors thanks to the impedance mismatch between the short-circuited and free propagation velocities. A particular example of wide band devices corresponds to SAW-tag for which an impulse electromagnetic excitation is converted to acoustic propagation by the interdigitated transducer (IDT), followed by the propagation and reflection of the surface wave by mirrors operating at Bragg conditions, the acoustic wave being transformed again in an electromagnetic signal to detect. In the case of resonators, an harmonic excitation is converted as well in acoustic propagation confined between Bragg mirrors within the IDT region which condition the capability of the device to deliver a long term decayong response once the harmonic interrogation stopped. In both cases, the electromechanical conversion efficiency is a crucial parameter, controling the interrogation efficiency and distance. However, one can note that the sensitivity of resonators built on highly coupled material (such as $LiNbO_3$) to resistive load prevents their actual implementation, whereas weakly coupled substrates (quartz) do not allow for long distance (more than a few cm) interrogation of delay lines.), quartz or

Throughout this presentation, we shall keep in mind the purpose of extending the basic physical principles of acoustic transducer probing by RADAR-like electronics to embedded electronics also known as readers. Wide use of this technology is only possible if low-power, affordable electronics become available to non-expert users. This objective will define some of the interrogation method constraints: basic signal processing and low sampling rate ($<$1 Msamples/s) will be favored for compatibility with mainstream microcontroller performances (Friedt *et al.*, 2010). We will successively demonstrate basic principles of SAW (narrowband) resonator and (broadband) delay line probing using hardware operating respectively in the 434 MHz and 2450 MHz ISM (Industrial, Scientific and Medical) unlicensed radiofrequency bands.

2. Time-domain resonator response

Resonators are most often considered for their spectral characteristics, namely impedance at resonance and width of the resonance (related to the quality factor Q through the operating frequency f divided by the width at half height of the real part of the admittance). Single-crystal piezoelectric substrates have been used for a long time for resonator manufacturing since the electro-mechanical response of the device provides properties (high inductance yet low motional resistance) hardly accessible with passive electronic components (Vig, 2002). Rather than considering resonators as frequency selective components in an oscillator configuration, we here consider the time domain response of a resonator and demonstrate the loading and unloading of electromagnetic energy stored as acoustic energy thanks to the piezoelectric substrate.

Resonators are characterized by two properties we will be interested in: a resonance frequency and a quality factor. The latter is representative of the losses as the device oscillates and dissipates during each period a fraction of the stored energy in its environment: while Q-factor monitoring has generated intense research activity (Rodahl *et al.*, 1995) in biosensing and thin-film characterization in the so-called micro-balance application, it has hardly been used in wireless sensing. On the other hand the resonance frequency of a surface acoustic wave resonator is strongly affected by the physical environment of the transducer (temperature, stress) and will be the quantity of interest. The two classical frequency identification techniques are recording the impulse response of the device excited by a broadband signal and extracting the resonance frequency by performing a Fourier transform on the returned signal, or frequency-sweep of the emitted pulse carrier followed by recording the frequency dependent response of the device, and identifying the admittance maximum. The former technique, although demonstrated experimentally (Hamsch *et al.*, 2004; Beckley, Kalinin, Lee, Volyansky, 2002; Beckley, Kalinin, Lee, Voliansky, 2002) requires significant computation capability and will not be considered here. Rather, we will record a single voltage at the output of a radiofrequency power detector representative of the energy loading in the resonator for each frequency as the signal generated by the RADAR-like reader is swept in the 434-MHz ISM band (Friedt *et al.*, 2010).

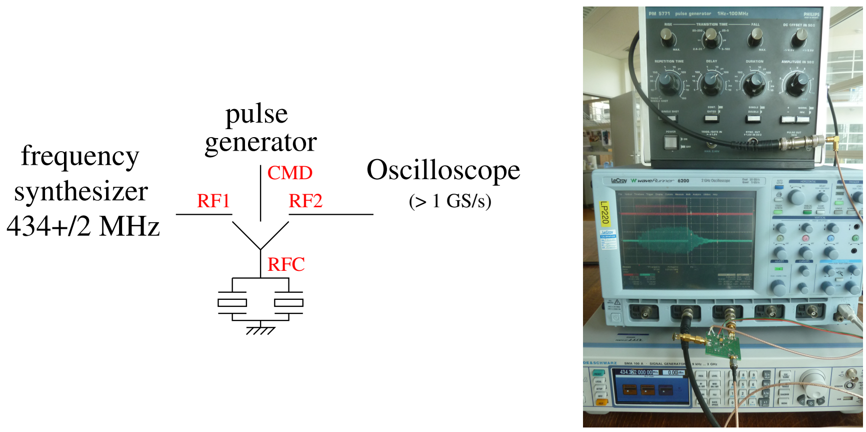

Figure 3. A switch is controlled by a pulse generator in order to alternate loading and unloading phases of a dual resonator SENSeOR sensing element. The pulsed loading allows for visualizing the rising voltage while in the unloading phase, the switch remains connected to the oscilloscope

The time constant of the loading and unloading resonator (piezoelectricity being linear, both operations are symmetrical) is Q/π periods. A high enough quality factor is needed for wireless sensing in order to distinguish the sensor response from clutter (very-low Q passive reflectors): low Q reflectors such as dielectric passive cooperative targets will only exhibit minor effects with respect to clutter and will be difficult to use as sensors. On the other hand, the interrogation duration is proportional to the time constant $\tau = Q/(\pi \cdot f)$ while the signal decay is observed as $\exp(-t/\tau)$ so a tradeoff is met when τ is long enough to get rid of clutter while higher Q only yields slower interrogation durations with little gain in terms of interrogation range. Typical sensors exhibit a quality factor of 10^4 at 434 MHz or a time constant of 7.3 μs. Asymptotic behavior is considered reached when 99% of the asymptotic limit is reached, or 5 time constants. Hence, probing the resonator response for a single frequency step requires $2 \times 5 \times 7.33 = 73$ μs. Since at least 3 points must be recorded within the resonator bandpass $f/Q \simeq 45$ kHz to guarantee resonator detection, the 1.7 MHz wide 434 MHz centered ISM band must be swept with 113 frequency steps. Hence, the total measurement duration lasts $113 \times 73 = 8250$ μs or a refresh rate of the detected resonance frequency of 121 Hz in the absence of additional averaging.

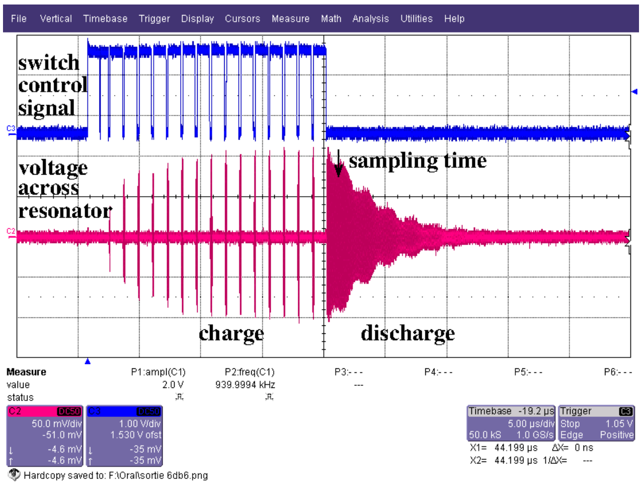

Figure 4. Dual-resonator (433.5 MHz and 434.5 MHz nominal frequencies) sensor loaded and unloaded close to one of the resonances. Top: radiofrequency switch control signal, with a loading phase chopped in order to observe on the oscilloscope the energy loading in the resonator. Bottom: voltage observed across the resonator with a 50 ohm loaded radiofrequency (10 Gsamples/s) oscilloscope input

In this example (Figure 3), the loading phase is chopped between the RF synthesizer and the oscilloscope (the resonator being on the common point of the switch), in order to allow for the visualization of the exponentially rising voltage observed on the resonator. During the unloading phase, the switch is kept in a constant position in which the exponentially decaying voltage is observed (Figure 4). In the case of a wireless sensing approach, either the Fourier transform is computed on the received signal – yet the short time constant (in the tens of microseconds range) makes a high resolution difficult to achieve and requires fast periodic acquisitions as well as multiple averages to converge. On the other hand, if the emitted signal is at a known well-defined frequency (*i.e.* pulse narrower than the inverse of the time constant τ defined previously), then a single sample at a given time after the switch has connected the resonator to the oscilloscope is sufficient to characterize the resonance position. This is the approach selected in the SENSeOR wireless reader, aimed at minimizing the hardware requirements to a fast track-and-hold (<1 μs time constant), as presented in the next section.

3. Resonator wireless sensing

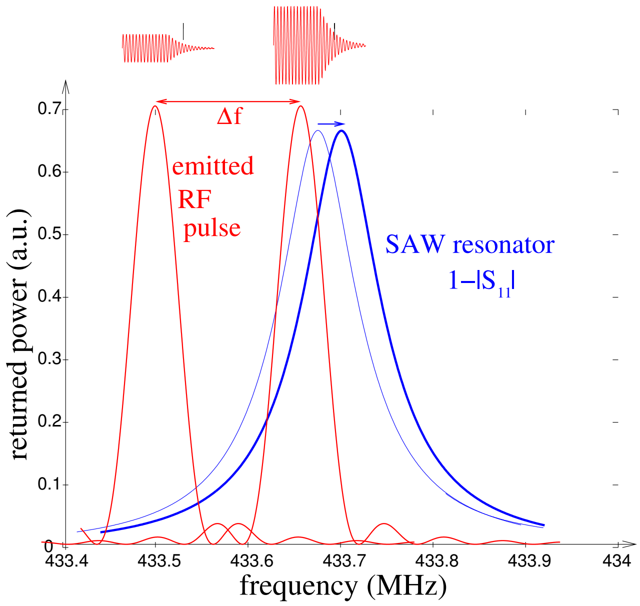

Figure 5. Principle of a frequency-sweep resonator characterization

We present in this section (Figure 5) results of an implementation of an embedded wireless reader based on the frequency sweep (Figure 6) and measurement of the returned power approach (Figure 7). In this application, a known emitted frequency allows for a simple reception stage made solely of a broadband power detector whose output voltage is visible on the oscilloscope display. A single sample is recorded at a given time after switching the antenna from emission to reception: the received power is representative of frequency difference between the emitted pulse carrier and the sensor resonance frequency. Each pulse is long enough for the spectral width of the emitted pulse to be narrower than the resonator bandwidth. By recording a single measurement of the radiofrequency received power after clutter has faded out and the radiofrequency switches settled (about 1 μs after switching from emission to reception), the transfer function of the resonator and associated transmission line between the reader and the sensor is recorded. The maximum returned signal is close to the resonance frequency and has actually been observed to be at the same frequency as the minimum of the magnitude of the reflection coefficient S_{11} since the ability of the resonator to send energy back to the reader is related to its ability to initially recover the pulse energy sent by the reader. The use of a Direct Digital Synthesizer as radiofrequency source allows for versatile frequency selection and hence implementation of various algorithms optimized for measurement resolution (Droit *et al.*, 2010) or speed (Friedt *et al.*, 2012). As an example of such an improvement, rather than sweeping the whole allocated frequency band once the resonance frequency has been identified, and assuming it does not change significantly between successive interrogation sequences (valid for example for temperature measurements which are usually slowly varying processes with respect to the measurement refresh rate), then only three measurements are needed to track the resonance frequency, yielding a refresh rate of $1/(3 \times 73\ \mu\mathrm{s})$=4.6 kHz. If a slower refresh rate is targeted, such fast sampling allows for multiple averages to be performed and the detected resonance frequency value to decrease as the square root of the number of averages.

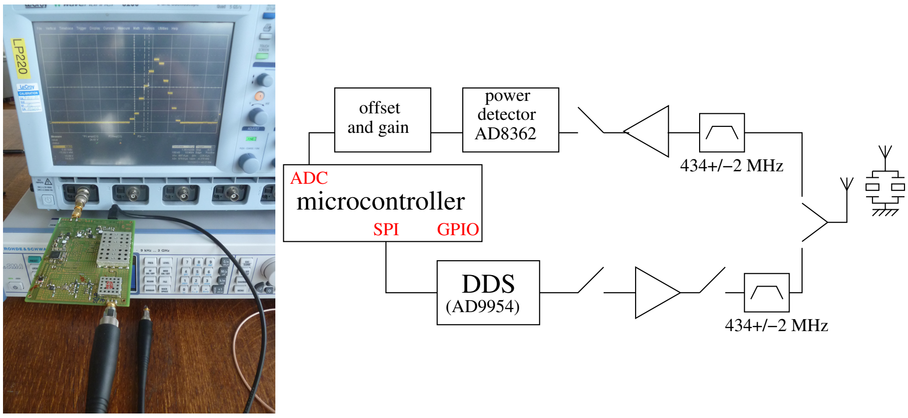

Figure 6. Right: schematic of the SENSeOR interrogation unit. Left: an analog output connected to a digital-to-analog converter provides the raw values of the recorded radiofrequency power at the power detector output as the frequency is swept along the ISM band. The resonance is visible as a maximum of stored power returned to the receiver stage

One fundamental aspect of resonance frequency measurement is the stability of the reference oscillator in order to guarantee that the measured frequency shift is indeed due to the sensor acoustic propagation property change rather than the reader local oscillator drift. In order to reduce the influence of unwanted correlated noise sources on the sensor side (radiofrequency propagation channel variation, sensor aging) and local oscillator stability requirement, a differential approach in which *two* resonators are located on the sensing element – one reference with little variation with respect to the physical quantity under investigation and one measurement resonator exhibiting a large sensitivity – is mandatory. In this approach, a resonance frequency *difference* of about 1 MHz is measured as opposed to an absolute frequency around 434 MHz, hence reducing the stability requirements on the local oscillator by a 434 factor. Typical targeted frequency identification resolution are in the sub-kHz range in order to measure, for example, a temperature with sub-K resolution. This requirement is deduced from the radiofrequency regulation compliance requirement: a sensor operating in a 300 K range and confining the signal within a 1.5 MHz band (*i.e.* keeping some distance from the ISM band boundaries) will exhibit a sensitivity of 5000 Hz/K and hence 0.1 K resolution requires a resonance frequency identification with 500 Hz resolution. This resolution is achieved following a parabolic fit (second order Taylor approximation) of the recorded transfer function around the resonance, with a resonance frequency identification improvement equal to the radiofrequency detected power signal to noise ratio of typically 100 (Friedt *et al.*, 2010).

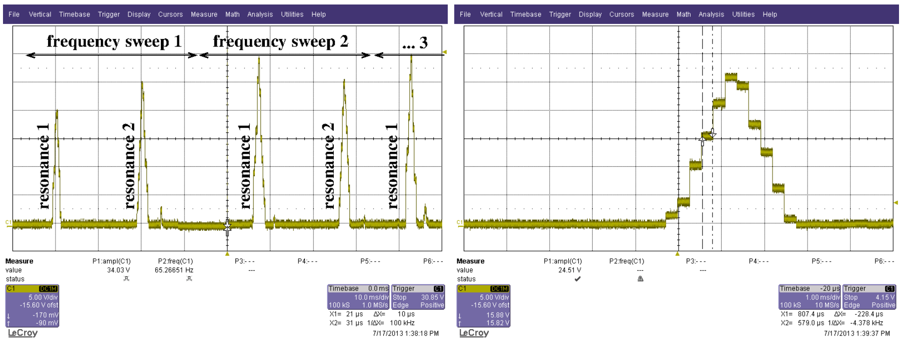

Figure 7. Returned power as a function of frequency (DDS frequency sweep as a function of time). Left: the measurement is repeated multiple times for averaging, each 128-sample measurements requiring 10.0 ms. Right: zoom on the power returned by one of the resonators, emphasizing the discrete frequency steps. Each step is about 73 µs long to allow for the resonator loading and unloading

4. Delay line wireless sensing

As opposed to the narrowband resonator, the delay line is designed as a broadband sensor characterized in the time domain. In a pulsed RADAR approach, short pulses (typically less than 100 ns long, or at least 10 MHz bandwidth) are generated, converted to an acoustic wave by the inverse piezoelectric effect thanks to interdigitated electrode (IDT) patterned on an appropriate substrate (typically lithium niobate or tantalate since high electro-mechanical coupling is needed) and reflected by electrodes patterned on the single crystal piezoelectric substrate acting as mirrors. The time of flight is roughly extracted by searching for the maximum of the reflected power, but it is well known (Kuypers *et al.*, 2008; Reindl *et al.*, 2003) that analyzing the phase of the returned pulse is mandatory for an precise measurement of the physical quantity changing the acoustic velocity.

Since there is a one to one relationship between the time domain and spectral domain response of a transducer through the Fourier transform, an efficient probing mechanism has been identified through the FMCW RADAR (Charvat *et al.*, 2012) (Figure 8). This RADAR implementation has been used when high output refresh rate is not mandatory and when simple and robust hardware is needed, such as in space probe landing missions (Trautner *et al.*, 2003). In this approach, a linearly swept frequency source (Voltage Controlled Oscillator – VCO) probes the sensor over its operating frequency range (Figure 9): the emitted frequency range is defined by the delay line IDT spacing and number of finger pairs in the electrode – the larger the number of finger pairs, the narrower the frequency band triggering a sensor response. The carrier frequency is eliminated by mixing the returned signal with the local oscil-

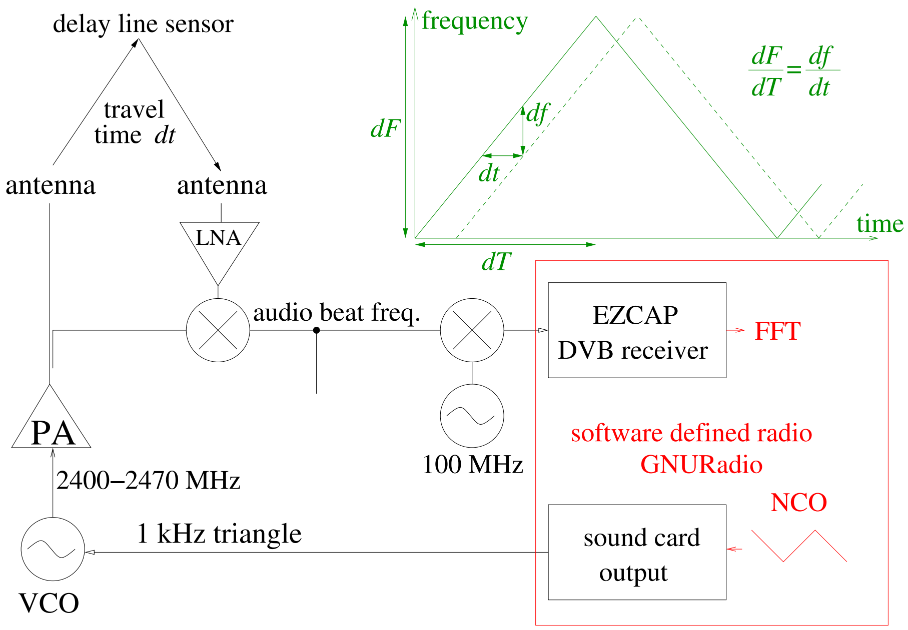

Figure 8. Basics of FMCW interrogation. In this implementation, a personal computer based setup is used rather than a high-end oscilloscope with Fourier transform capability: the software defined radio (SDR) approach provided by the GNURadio opensource software environment provides the flexibility needed for fast prototyping

lator: since the two-way trip of the electromagnetic wave lasts τ, the local oscillator was shifted by a frequency offset proportional to τ. The longer the echo took to return, the larger the frequency offset and the larger the beat frequency value. Indeed, as a frequency span ΔF defined by the bandpass of the sensor is swept over a time T, a beat frequency δf proportional to the time delay τ is given by

$$\frac{\Delta F}{T} = \frac{\delta f}{\tau}$$

A Fourier transform on the returned signal exhibits a few peaks whose distance from DC are representative of the time delay of the echoes (Figure 10). The various figures of the experiment emphasize the need for averaging since the bare Fourier transform over a single VCO period does not exhibit measurable peaks (Figures 10 and 11: averaging over multiple periods (64 here – pink curves) is mandatory since the signal to noise ratio is insufficient to detect the echoes on the orange (raw Fourier transform) curves). The main advantages of this approach are the low sampling rate of the signal recovered at the output of the mixer since a practical calculation for typical delays τ less than 4 μs and bandwidths of the order of $\Delta f = 50$ MHz, a sweep rate $T = 1/200$ s yields beat frequencies of the order of 40 kHz, much more accessible than the tens of MHz needed in the pulsed mode RADAR approach. The computational power requirement of the Fourier transform has become readily available with modern digital electronics. The low beat frequency is compatible for prototyping purposes with sound card recording for a personal computer based prototyping setup in which all digital computations are performed in a software defined radio (SDR) environment (Figure 8) (Friedt, 2013).

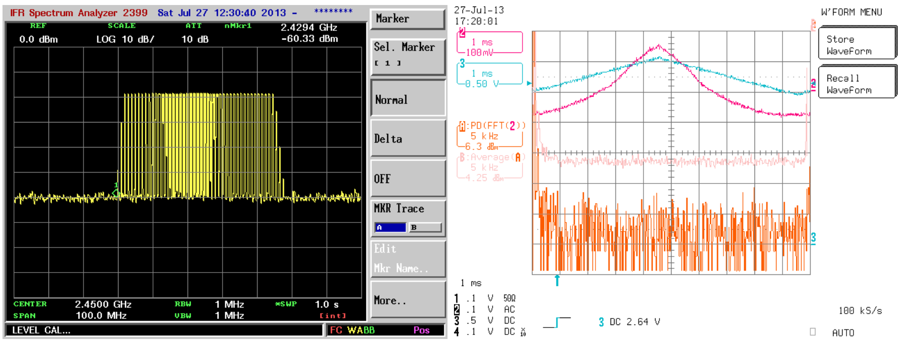

Figure 9. Left: emitted spectrum. Right: returned signal in the absence of sensor as the VCO frequency is swept. Only clutter is visible, no echo due to the acoustic delay line is expected. Orange is the Fourier transform of the magenta curve, pink is a running average over 64 samples of the orange curve. Blue is the VCO drive signal. One period of the FMCW VCO sweep is visible on this graph

In this example, the raw mixer output is sampled on a 50-ohm oscilloscope input, no low frequency low-pass filter and amplifier has been added as would be needed for a reasonable interrogation range. Nevertheless, even with such a simple setup, an interrogation range of 30 cm is easily reached when averaging 64 curves (interrogation duration from 0.3 to 1 s depending on the VCO sweep rate).

The main drawback of the FMCW approach (Figure 11, left) is the time needed for averaging to extract the signal from the noise in the Fourier transform. We have already seen that the frequency offset, which must not rise above half of the sampling frequency, is defined as $\delta f = \frac{\Delta F}{T} \cdot \tau$. On the other hand, sampling over a large number of periods T is needed on the one hand to improve the Fourier transform resolution (and hence the range resolution), and on the other hand to improve the signal to noise ratio by averaging. The refresh rate is thus independent of T and the interrogation duration is defined by the targeted interrogation range and hence number of averages needed to extract the peaks from noise.

The significance of the phase noise and windowing on the recorded signal is best illustrated in Figure 10, right. Lowering the sweep rate of the VCO, the beat frequency moves to lower values and becomes drowned in the low-frequency noise of the oscillator. Hence, the VCO sweep rate is optimized to use at best the available recorder bandwidth, while making sure that the beat frequency never reaches half of the sampling rate (Figure 11, right).

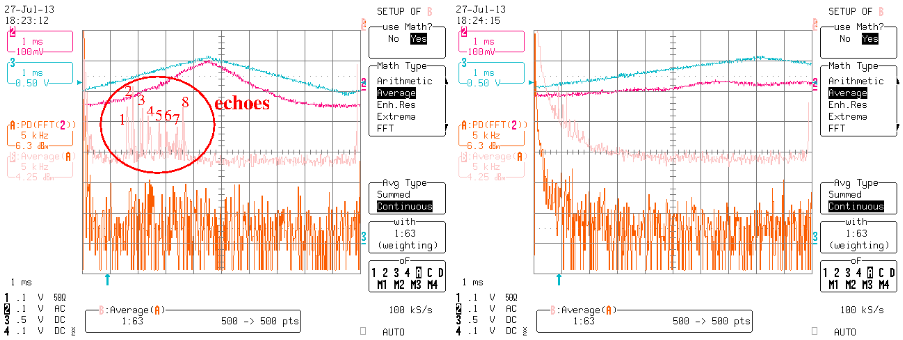

Figure 10. Left: 100 Hz sweep rate, sensor located over the tin-can antennas. Right: 50 Hz sweep rate, sensor located 30 cm over the antennas in order to prevent the strong clutter reflections over the antenna from hiding the sensor response

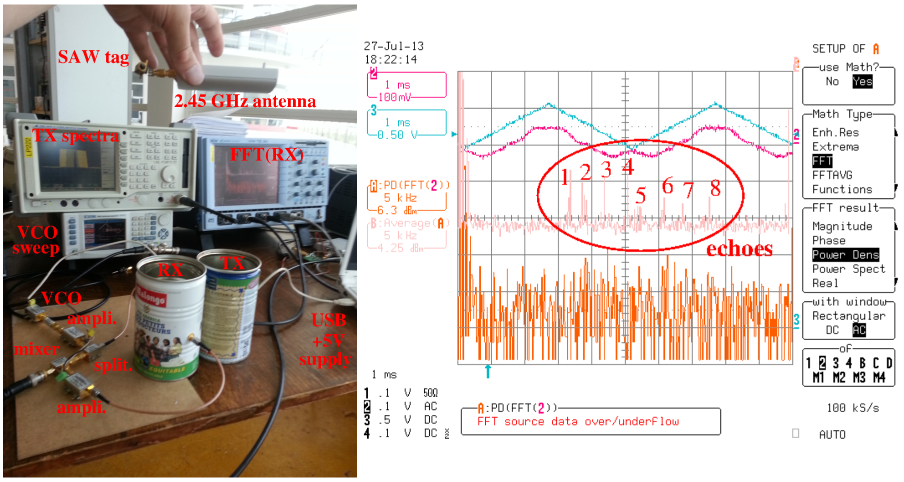

Figure 11. Left: picture of the experimental setup for wireless delay line sensing using an FMCW approach. The sensor is manually held at a distance of 30 cm above the antennas. Right: recorded signals as the VCO is swept at a rate of 200 Hz and the sensor is located 30 cm away from the antennas. The signal of interest has been moved to the middle of the Fourier transform frequency range

Hence, the free parameters in this setup are the VCO offset (moving the emitted chirp away from the bandpass of the sensor will reduce the returned signal power), VCO sweep rate, VCO excursion (too wide a frequency sweep range yields increased effect of the non-linear frequency v.s voltage relationship), VCO drive signal shape and its effect on the Fourier transform displayed on the oscilloscope, as well as averaging factor on the oscilloscope (longer averages improve signal to noise ratio and hence range, but reduce output refresh rate).

5. Application example

One typical application lies in preventive monitoring of rotating parts. Figure 12 exhibits the temperature measurement resulting from a sensor located on a 120-kW power electrical motor with the reader connected to an antenna attached to the stator. The challenges met in this particular application are:

– lack of space between rotor and stator for complete angular coverage of the reader and sensor antennas. In this case, two dipoles were connected respectively to each element of the measurement system, resulting in 180^o angular coverage. For a robust application insensitive to environmental condition, we did not select a full 360^o coverage which exhibits strong sensitivity to surrounding parameters (moisture level, addition of parasitic elements around the antennas, mounting uncertainty). Nevertheless, excellent measurements are observed up to at least 4500 rpm, the maximum speed at which this motor model could be operated, thanks to the short interrogation duration,

– random electrical noise due to the power electrical motor operating in such a close vicinity to the reader antenna. Spikes were observed on the radiofrequency power receiver which initially prevented useful measurements to be performed. The addition of software filters using the *a-priori* knowledge of the expected resonator returned signal response shaped allowed for the short noise pulses to be filtered out and only useful measurements to be recorded,

– since a running average is performed on 8 to 16-samples, a standard deviation criterion rejects datasets which are not within a pre-defined resolution value.

Similar applications include tire temperature monitoring *within* the rubber fabric (as opposed to surface temperature measurement) which were successfully performed up to 280 km/h driving speeds (Figure 13). At such a velocity and an angular coverage of the reader antenna with respect to the dipole antenna connected to the sensor and embedded in the tire rubber of about 60^o, the visibility duration of the sensor by the reader is about 36 ms, or much more than the minimum duration of 8.2 ms described earlier in the resonator probing section (chapter 2). 5 sensors are located at various positions along the tire section, measuring the tire rubber temperature from the sides to the tread. Two antennas located at two different positions around the tire and connected to a single multiplexed reader aim at improving the refresh rate to better than 2 Hz. In such a configuration, the asychronous serial link (RS232-compatible) becomes the limiting factor defining the data transfer rate to the user and a microcontroller-controled analog output (digital to analog converter) is favored in order not to limit the refresh rate.

Due to the low entropy of resonators, sensor differenciation can only be performed through the resonance frequency position, with the easiest strategy being to allocate pre-defined frequency bands to each resonator. In this application, each temperature sensor was allocated a 2 MHz bandwidth (1 MHz for the reference resonator and 1 MHz for the measurement resonator), well beyond the ISM band regulations. Each frequency band is sequentially probed by the reader and, were the sensor visible

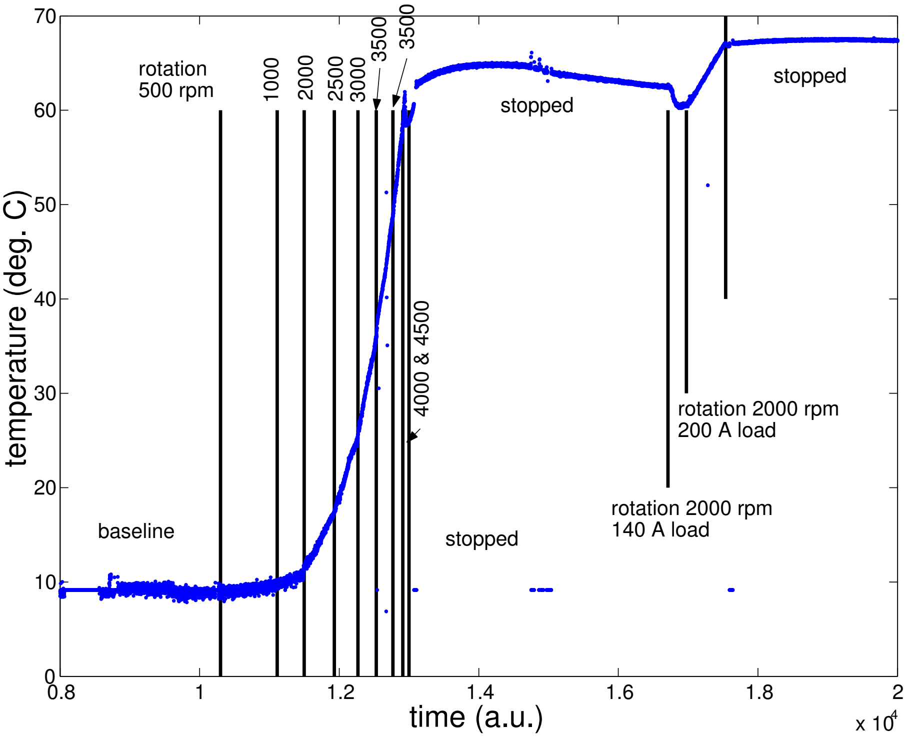

Figure 12. Temperature measurement on a rotating electrical motor whose ball-bearing is damaged, yielding excessive heating of the rotor to which the dual-resonator acoustic sensor is attached

from the reader and this particular band is being scanned, the resonance frequency is returned to the user if the receiver power is above a threshold level. This frequency domain multiplexing, in addition to the antenna multiplexing, is the cause of the rather low refresh rate which nevertheless remains meaningful for the slowly varying temperature measurement.

Thanks to the flexibility of the software defined reader implemented on a versatile hardware, algorithms are optimized for various signal characteristics but most significantly updates are brought on application sites where radiofrequency disturbances are not necessarily well identified prior to visiting an industrial installation.

6. The quartz tuning fork

This presentation has so far focused on Ultra-High Frequency (UHF) radiofrequency devices operating above the 300 MHz range, in compliance with the ISM-band regulations compatible with far-field interrogation strategies. It is yet relevant to remind the reader of the acoustic transducer basics – best suited for training and teaching

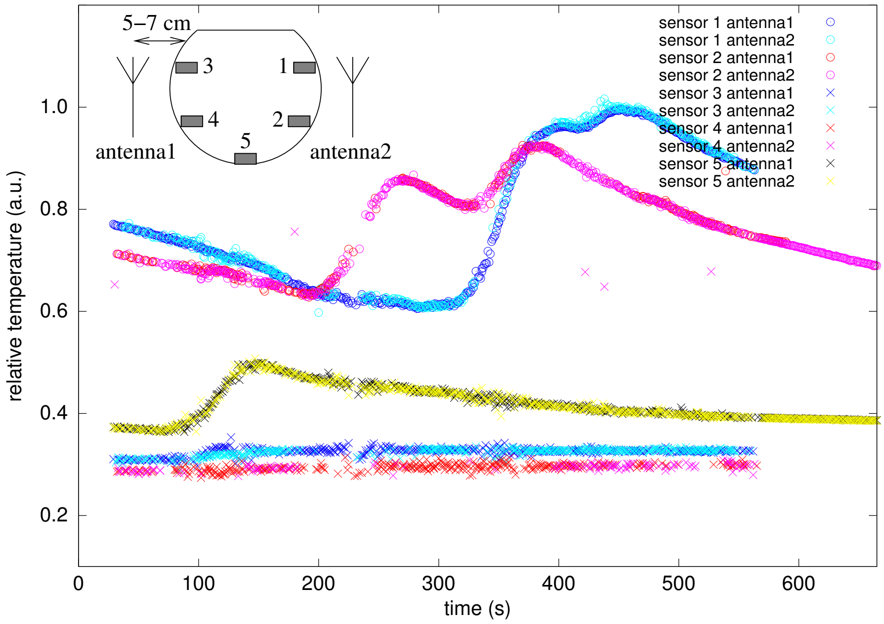

Figure 13. Temperature measurement on a tire operated from 0 to 200 km/h in a straight line and cambered at angles ranging from 20 to 55^o at 50 km/h. Top left: schematic of the tire cross section indicating the five sensor positions in the rubber

purposes – as implemented in the quartz tuning fork as found in any so-called "quartz watch" or most digital electronic equipment.

The quartz tuning fork is arguably one of the most common piezoelectric micro-electromechanical systems, generating the beat signal of most modern watches, and yet is hardly acknowledged for the feats it performs. We propose some basic introduction to the 32768 Hz tuning fork as an introductory topic for illustrating electro-mechanical piezoelectric resonators (Friedt, Carry, 2005; 2007).

The success of the electro-mechanical transducer lies in the equivalent electronic circuit component values which are unreachable using coils and capacitors, especially in such a compact format. With a quality factor in the 80 000 range when packaged, dropping to a few thousands once the vacuum sealed package is broken open, the oscillator typically exhibit a relative stability of 10^{-9} at 1 s and a turnover temperature around wrist temperature of 30^{o}C. Tuning forks have found wide uses beyond the time keeping application, including acting as a exquisitely sensitive transducer in scanning probe microscopy aimed at keeping a fine probe at a nanometric distance from a surface (Karrai, Grober, 1995).

Far field wireless sensing of such low frequency devices is not possible since the electromagnetic wavelength at the 32768 Hz frequency is the 10 km range. Al-

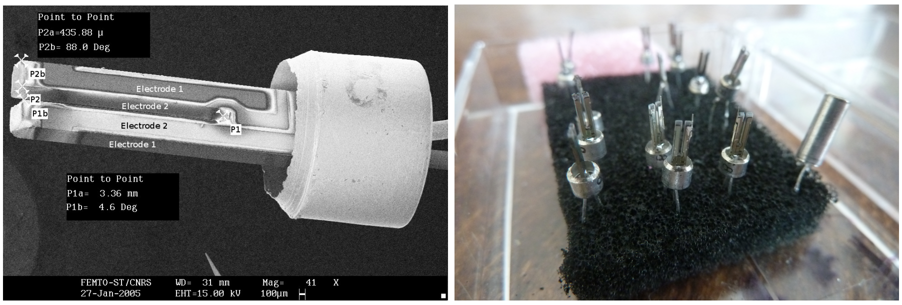

Figure 14. Left: scanning electron microscope image of a quartz tuning fork. Notice the shape of the electrodes, patterned on all external sides of the prong, to generate the appropriate electric field lines in order to favor the first anti-symmetric vibration mode (courtesy of É. Carry, FEMTO-ST). Right: unpackaged quartz tuning forks, here fitted with sharp tips for scanning probe microscopy applications

though 125 kHz devices act as RFID, close coupling is needed and do not allow for far field, fast measurements on mobile objects. An interesting approach is to use a high frequency transducer modulated by the low frequency resonator (Ostertag, Schacherbauer, 2004), but the introduction of non linear passive electronic components to demodulate the incoming probe signal and modulate the antenna impedance means loosing most of the interesting aspects of SAW transducers. The high quality factors of such devices means they are unsuitable for fast measurements since their time constant is in the second range: scanning probe microscope applications actually require some quality factor tuning by actively injecting energy out of phase when fast scanning rates are required (Humphris *et al.*, 2003; Antognozzi *et al.*, 2003; Humphris *et al.*, 2000). The interesting aspect of this approach is to continuously tune, by injecting energy in phase or out of phase, the oscillator condition as an asymptotic condition in which the in-phase injected energy compensates for the losses (Friedt, Carry, 2007).

7. Conclusion

Using acoustic transducers as passive sensors interrogated through a wireless link is promoted by demonstrating some basic laboratory experiments aimed at becoming familiar with the basics of RADAR-like hardware designed to record relevant quantities of resonator or delay lines used to measure physical quantities. Beyond the demonstration of some basic physics principle (resonator loading and unloading), a practical delay line interrogation unit is demonstrated requiring little dedicated hardware. Converting this laboratory-based experiment to an embedded device meeting size and power consumption requirements is a technically simple yet time consuming activity since the proposed designs only require low bandwidth sampling rates compatible with most microcontroller implementations.

We have demonstrated practical applications of wireless passive acoustic sensors in fields in which no other sensor is usable, namely rotating parts (no wired configuration) in which no maintenance is possible after sensor installation, either because the sensor is no longer accessible (buried in the rubber tire fabric) or because the motor cannot be stopped for battery replacement.

Acknowledgements

These experiment were developed as a part of the European Frequency and Time Seminar (EFTS) laboratory training (http://efts.eu), with the help of the Oscillator IMP platform and partially sponsored by the First-TF network.

Bibliography

Antognozzi M., Szcelkun M., Humphris A., Miles M. (2003). Increasing shear force microscopy scanning rate using active quality-factor control. *Appl. Phys. Lett.*, Vol. 82, pp. 2761–2763.

Bao X. Q., Burfhand W., Varadan V., Varadan V. (1987). SAW temperature sensor and remote reading system. In *IEEE ultrasonics symposium*, pp. 583–585. Denver, CO, USA.

Beckley J., Kalinin V., Lee M., Voliansky K. (2002). Non-contact torque sensors based on saw resonators. In *IEEE international frequency control symposium and PDA exhibition*, pp. 202–213.

Beckley J., Kalinin V., Lee M., Volyansky K. (2002). Non-contact torque sensors based on SAW resonators. In *IEEE international frequency control symposium*, pp. 202–213. New Orleans, USA.

Bruckner G., Stelzer A., Maurer L., Biniasch J., Reindl L., *et al.* (2003). A high-temperature stable SAW identification tag for a pressure sensor and a low-cost interrogation unit. In *11th international sensor congress (SENSOR)*, pp. 467–472. Nuremberg, Germany.

Buff W., Klett S., Rusko M., Ehrenpfordt J., Goroli M. (1998, September). Passive remote sensing for temperature and pressure using SAW resonator devices. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 45, No. 5, pp. 1388–1392.

Charvat G., Fenn A., Perry B. (2012). The MIT IAP radar course: Build a small radar system capable of sensing range, Doppler, and synthetic aperture (SAR) imaging. In *IEEE radar conference*, pp. 138–144. (http://ocw.mit.edu/resources/)

Cunha M. P. da, Lad R., Moonlight T., Bernhardt G., Frankel D. (2008). High temperature stability of langasite surface acoustic wave devices. In *IEEE ultrasonics symposium*, pp. 205–208. Beijing, China.

Dong Y., Cheng W., Wang S., Li Y., Feng G. (2001). A multi-resolution passive SAW chemical sensor. *Sensors and Actuators B*, Vol. 76, pp. 130–133.

Droit C., Martin G., Ballandras S., Friedt J.-M. (2010). A frequency modulated wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement. *Rev. Sci Instrum.*, Vol. 81, No. 5, pp. 056103. (Available at http://jmfriedt .free.fr)

Friedt J.-M. (2013). GNURadio as a digital signal processing environment: application to acoustic wireless sensor measurement and time & frequency analysis of periodic signals. In *IEEE international frequency control symposium.* Prague, Czech Republic.

Friedt J.-M., Carry É. (2005, December). Introduction au diapason à quartz. *Bulletin de l'Union des Physiciens*, Vol. 879.

Friedt J.-M., Carry E. (2007). Introduction to the quartz tuning fork. *American Journal of Physics*, pp. 415–422.

Friedt J.-M., Droit C., Ballandras S., Alzuaga S., Martin G., Sandoz P. (2012, May 1st). Remote vibration measurement: a wireless passive surface acoustic wave resonator fast probing strategy. *Rev. Sci. Instrum.*, Vol. 83, pp. 055001. (Available at http://jmfriedt.free.fr)

Friedt J.-M., Droit C., Martin G., Ballandras S. (2010). A wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement. *Rev. Sci. Instrum.*, Vol. 81, pp. 014701. (Available at http://jmfriedt.free.fr)

Friedt J.-M., Rétornaz T., Alzuaga S., Baron T., Martin G., Laroche T. *et al.* (2011). Surface acoustic wave devices as passive buried sensors. *Journal of Applied Physics*, Vol. 109, No. 3, pp. 034905. (Available at http://jmfriedt.free.fr)

Friedt J.-M., Saintenoy A., Chrétien S., Baron T., Lebrasseur E., Laroche T. *et al.* (2013). High-overtone bulk acoustic resonator as passive ground penetrating RADAR cooperative targets. *J. Appl. Phys.*, Vol. 113, No. 13, pp. 134904.

Hamsch M., Hoffmann R., Buff W., Binhack M., Klett S. (2004). An interrogation unit for passive wireless SAW sensors based on Fourier transform. *IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 51, No. 11, pp. 1449–1456.

Humphris A., Hobbs J., Miles M. (2003). Ultrahigh-speed scanning near-field optical microscopy capable of over 100 frames per second. *Appl. Phys. Lett.*, Vol. 83, pp. 6–8.

Humphris A., Tamayo J., Miles M. (2000). Active quality control in liquids for force spectroscopy. *Langmuir*, Vol. 16, pp. 7891–7894.

Karrai K., Grober R. (1995). Piezoelectric tip-sample distance control for near field optical microscopes. *Appl. Phys. Lett.*, Vol. 66, pp. 1842–1844.

Kuypers J., Reindl L., Tanaka S., Esashi M. (2008). Maximum accuracy evaluation scheme for wireless SAW delay-line sensors. *IEEE Trans. Ultrason. Ferroelecr. Freq. Control.*, Vol. 55, No. 7, pp. 1640–1652.

Ostertag T., Schacherbauer W. (2004). *Coupling of a sensor element to a transponder.* WO/2004/049280.

Pohl A., Steindl R., Reindl L. (1999, December). The "intelligent tire" utilizing passive SAW sensors – mesurement of tire friction. *IEEE Transactions on Instrumentation and Measurement*, Vol. 48, No. 6, pp. 1041–1046.

Reindl L., Shrena I., Richter H., Peter R. (2003). High precision wireless measurement of temperature by using surface acoustic wave sensors. In *IEEE freq. control symposium.*

Rodahl M., Höök F., Krozer A., Brzezinski P., Kasemo B. (1995). Quartz crystal microbalance setup for frequency and Q-factor measurements in gaseous and liquid environments. *Rev. Sci. Instrum.*, Vol. 66, No. 7, pp. 3924–3930.

Trautner R., Svedhem H., Lebreton J.-P., Plettemeier D., Floury N., Couzin P. (2003). FMCW radars for planetary landers: Lessons learned from the huygens radar altimeter. In *International planetary probe workshop.* Anavyssos, Greece.

Vig J. (2002). Quartz crystal resonators and oscillators for frequency control and timing applications – a tutorial. In *IEEE international frequency control symposium tutorials.* New Orleans, USA. (Available at http://www.umbc.edu/photonics/Menyuk/Phase-Noise/Vig-tutorial_8.5.2.2.pdf)

Wang W., Lim C., Lee K., Yang S. (2009). Wireless surface acoustic wave chemical sensor for simultaneous measurement of CO_2 and humidity. *J. Micro/Nanolith. MEMS MOEMS*, Vol. 8, No. 3, pp. 031306.