An Algorithm for Automating Fast and Accurate Measurements of the Resonance Frequencies of SAW sensors

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Within the context of probing acoustic wave resonators acting as wireless, passive sensors, we present an embedded interrogation unit and the associated algorithms, demonstrating the flexibility of a mostly software defined strategy. An ARM-7 based central processing unit synchronizes the narrow-band probing pulse emission, emission-to-reception switching, data sampling and data processing. Since each emitted pulse is independently defined with respect to its neighbours, flexible strategies are implemented aiming at fast (3 points needed to probe the resonant frequency, with a total duration less than 200 μs) and accurate ($\simeq$10 Hz resolution) techniques.

1 Introduction

Surface acoustic wave devices have been demonstrated as superior passive wireless sensors compared to passive Silicon-based sensors based on Radio-Frequency Indentification Devices (RFID) and with unique capabilities compared to active Silicon-based sensors, including longer lifetime (no need for local power supply) and wider temperature range [1, 2]. Amongst the two classes of acoustic sensors – delay lines and resonators – we focus on the latter since the narrow-band resonator is the only strategy compatible with the European 434 MHz ISM (Instrument-Scientific-Medical) band regulation [3, 4, 5, 6, 7]. Indeed, the 1.74 MHz wide available frequency range cannot provide the needed bandwidth for interrogating wide-band delay lines. This rather low ISM frequency range has been selected for manufacturing reproducibility, and imprived penetration depth of the electromagnetic wave in dielectric media compared to the higher 2450 MHz ISM band. The drawback of the 434 MHz band is the large – typically 35 cm long in open air – antenna associated with the sensor.

In order to probe these passive acoustic resonators, we are developing the associated radiofrequency (RF) interrogation unit (Fig. 1). The basic principle of this electronics is based on the RADAR strategy – with alternating emission and reception steps – with unique improvements such as emitting a probe pulse with a spectral width narrower than the resonator width at half height. Indeed, complying with ISM-band regulations not only requires the design of a narrowband transducer, but also the development of the associated interrogation strategy: wideband probe pulses followed by Fourier transform resonance frequency identification [8] are hardly applicable in such a narrow frequency range as the 1.74 MHz wide 434 MHz European ISM band. Nevertheless, even if using a frequency-sweep network analyzer approach reduces the requirements in terms of sampling rate and memory requirement, the global interrogation duration is increased due to the many frequency steps to be probed to accurately identify the resonance frequency. We here demontrate the use of a flexible approach [10] which needs only 3 probe pulses to identify the resonance frequency of the transducer, yielding a total measurement duration below 200 μs.

2 Hardware architecture

The core component of the interrogation unit is an ARM7-based microcontroller in charge of synchronizing all the measurement steps, storing and processing the resulting data, and communicating with the user through an asynchronous serial port (Fig. 2). An Analog Devices AD9954 Direct Digital Synthesizer (DDS), programmed

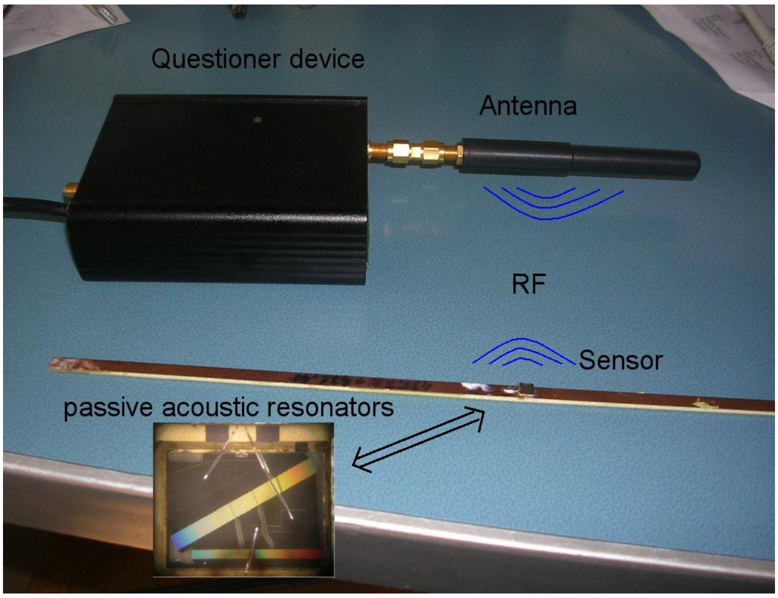

Figure 1: Wireless sensor, associated antenna and interrogation unit.

through a fast, local SPI bus, clocked by a 200 MHz clock, generates a signal in the 34±0.85 MHz range when complying with ISM regulations, although, the full range is 0-133 MHz, providing the needed flexibility to probe sensors performing out of the ISM band. This RF signal is mixed and band-pass filtered with a 400 MHz fixed frequency oscillator in order to generate the output frequency. A duplexer switches from the emission amplification circuit and the receiver circuit. Switching under microcontroller control to the receiving stage once the resonator is loaded, the received signal is band-pass filtered, amplified and fed to a wideband RF-power detector for digitization following an offset removal step and low-frequency amplification. Hence, for each emitted frequency, a single magnitude response is recorded, representative of the amount of energy stored in the resonator. ([9]).

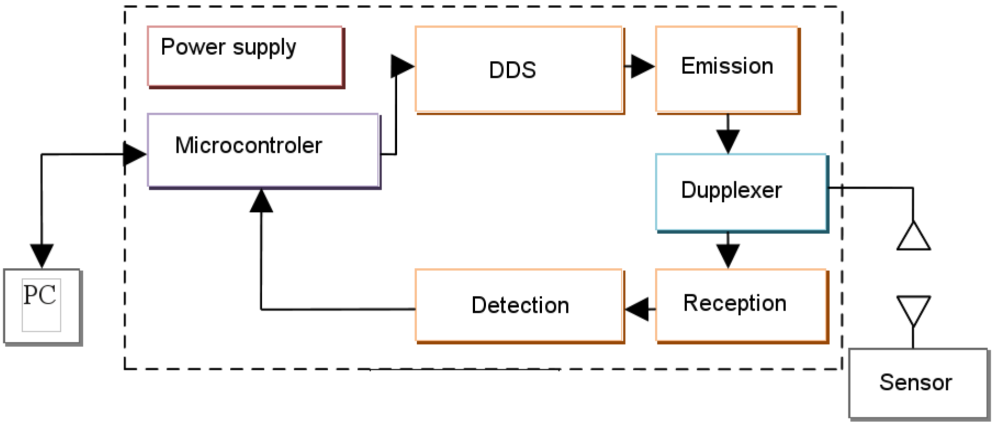

Figure 2: Synoptic of the hardware architecture

3 The resonance frequency identification

The purpose of the interrogation unit is to probe the resonator response at enough frequencies to identify its resonance frequency and, from this basic measuement, to compute the resulting physical quantity acting on the resonator. All measurements are differential: the sensor is made of two resonators in parallel, one of which exhibits a strong frequency drift as a function of the measurent quantity, whereas the other is mostly insensitive to the measured quantitity. A differential measurement is a fundamental aspect of robustness with respect to correlated noise sources, influence of the electromagnetic environment on the resonators (parasitic capacitances) and reduced influence of the local (interrogation unit) oscillator accuracy.

As an example of the targetted resolution, a temperature sensor working in the -20 to 160^{o}C range and complying with the 1.74 MHz wide ISM band exhibits a typical 2500 Hz/K first order temperature coefficient: this value is obtained by dividing the allocated frequency range in two equal parts for the reference and measurement resonators, and again dividing the resulting sub-bands by two to account for manufacturing uncertainties. Hence, measuring a temperature with 0.1 K resolution requires a differential frequency measurement resolution of 250 Hz.

The probe pulse duration is selected accounting to the resonator quality factor Q, to ensure that at least three frequencies are within the bandpass of the resonator. For resonators centered around f =434 MHz and $Q \simeq 10000$, the frequency step is 14.5 kHz. Sweeping the whole 1.7 MHz wide ISM band thus requires 117 sampling frequencies interrogation sequences according to the above criterion. The resolution of this coarse measurement is improved by using a second-order polynomial fit of the returned power data and identifying the resonance frequency as the parabola maximum, yielding a resolution improvement dependent on the signal-to-noise ratio but typically in the order of 100 in practical applications [9].

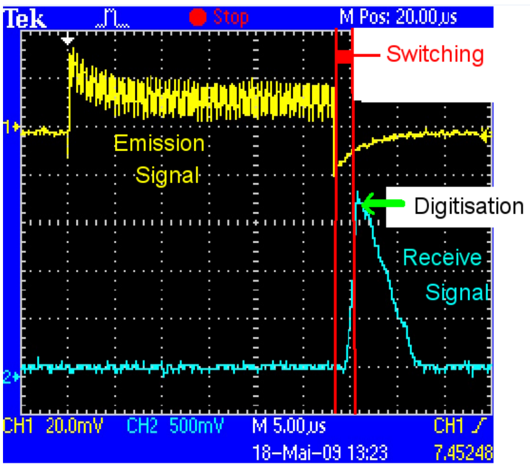

Figure 3: Probe pulse emission (yellow curve) and received signal at the wideband power detector output (blue curve).

In order to benefit from the highquality factor of resonators manufactured on single-crystal piezoelectric substrates, thespectral width of the emitted pulse must be narrower than the width at half height $f/Q = 40$ kHz of the sensor: each pulse must last at least 25 μs. Considering that the data storage and processing time, and including the time needed to configure the DDS, require another 30 μs, each frequency sampling lasts 60 μs. The basic strategy of sweeping the ISM band with 117 points thus requires 60×117=6700 μs. Such a duration is incompatible with applications in which either the sampling frequency must be higher because the time constant of the physical phenomenom is shorter (e.g. strain gauge on vibrating substrate application), or on moving or rotating sensor, because the visibility duration of the sensor by the interrogation unit is shorter.

This procedure is repeated for a multitude of frequency steps in the range of interest: emitting a pulse centered on a known frequency and recording the returned power for each emission, a power spectrum is generated consistent with the classical S_{11} network analyzer measurement (Fig. 4).

In order to avoid multiplying the number of probed frequencies to improve the resolution and hence increasing the interrogation time, we have presented previously [9] the digital processing steps used to improve the resonance

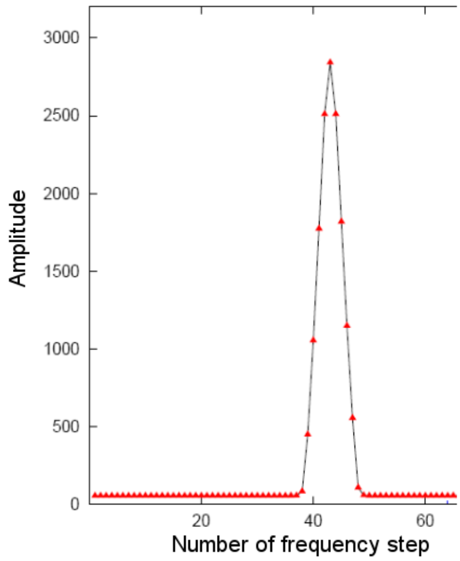

Figure 4: Experiemental wireless magnitude measurement as a function of frequency step for a typical resonator and associated interrogation unit configuration parameters as discussed in the text.

frequency identification resolution, using a second-order polynomial fit. As a quick reminder, considering three measurements at frequencies f_i, $i \in [1..3]$ equally spaced apart with steps Δf, and returned power measurements s_i, $i \in [1..3]$, we identify the resonance frequency f_0 by computing the unique parabola running through the experimental data and identifying the position of the polynomial maximum (Fig. 5):

$$f_0 = f_2 + \frac{\Delta f}{2} \times \frac{(s_1 - s_3)}{(s_1 + s_3 - 2 \times s_2)}$$

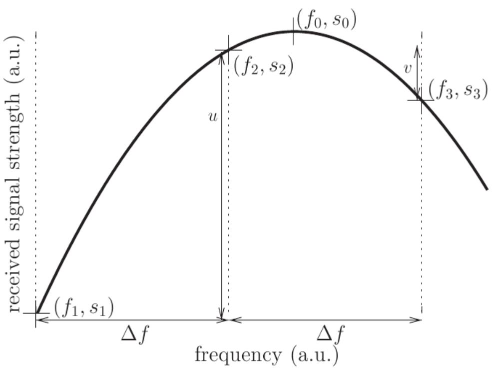

Figure 5: Polynomial fit of the experimental data (f_i, s_i), $i \in [1..3]$, in order to identify with improved resolution the resonance frequency f_0.

4 Reducing the number of sampled points and feedback strategy

So far we have considered that the frequency band in which the resonance of the sensor is known to occur is swept with 117 steps to make sure that at least three returned power measurements are representative of the resonance. Furthermore, the second-order polynomial fit of the experimental data induces a bias since the physics of the resonator, described by the Butterworth-van Dyke model and combined with parasitic components due to packaging and antenna, is only approximated by the parabola. This bias is dependent on the position of the resonance f_0 with respect to the fixed frequency comb f_i.

These issues are adressed using a three-point sampling method: indeed, since only three measurements are needed to perform the polynomial fit, the other 114 measurements are needed once for a coarse resonance position identification, but once f_0 has been identified, probing a narrow frequency-band around this position at $f_0 \pm \Delta f$ is sufficient to track the resonance frequency. This strategy removes the source of the bias since f_0 is no longer the result of a computation resulting from experimental measurements at fixed f_i, but the comb centered on the previous estimate of f_0 now tracks the resonance and aims at keeping one of pulses of the probe comb centered on f_0.

The resulting algorithm performs as follows (Fig. 4):

- a first preliminary step sweeps the ISM band, which is divided in two equal parts each including one resonance for the diffenrential measurement, with 2×64=128 points, a value slightly larger than the optimum 117 steps compatible with devices with higher quality factors,
- having accurately identified the resonance f_0 using the parabolic fit, a new sampling sequence focuses on only 3 points, f_0 and $f_0 \pm \Delta f$, and the same polynomial fit is performed on the resulting samples,
- the previous closed-control loop iterates as long as the returned power at f_0 is stronger than that at $f_0 \pm \Delta f$, meaning that the tracking strategy keeps the central probe pulse close to the resonance,
- in case the last condition is no longer met, or that the returned magnitudes are below a lower threshold value, the initial coarse sweep is triggered and the whole algorithm is reinitialized.

Considering that each interrogation step requires 60 μs, and since each resonance identification requires 3 measurements, once initialized this algorithm refreshes the measurement information at a rate of one value every $60 \times 3 \times 2 = 360$ μs for a dual resonance sensor. Furthermore, we typically average 16 measurements in order to reduce the measurement standard deviation: the resulting refreshing rate is 174 Hz. This result is 128/6=21 times faster than the "fixed frequency comb" strategy sweeping the while ISM band with 128 samples, and only limited by the asynchronous data communication rate to the user. Let us emphasize that this improved sampling rate is obtained in addition to the removal of the resonance frequency estimate bias source.

One major issue with closed-loop algorithms implementing a feedback of the next interrogation parameters using the result of the previous measurement is the identification of the resonance frequency loss, and triggering the algorithm reinitialization – a time consuming process which might not lock with quickly moving sensors. This issue arises when the sensor is only intermittently visible by the interrogation unit, as in the case of a sensor attached on a rotating part with an antenna coverage over a fraction of the perimeter. Another feedback control disruption source is the emission at the probed frequency range by another emitter: if this emission is stronger than the returned power from the resonator, the power detector saturates and f_0 is no longer identified. The lack of intermediate frequency (IF) and narrowband filtering in our baseband interrogation strategy, with a returned power equal to the integral of all returned signal within the frequency band of interest, yields a strong sensitivity to such disturbances.

Beyond the simple returned value threshold detection to check whether the probed frequency range still includes the resonane, a variance computation provides a reliable indicator of resonance loss when multiple measurements are performed for computing an average : too high a variance is a strong indicator of loss and then triggers the reinitialization of the algorithm.

Instead of reinitializing the algorithm and sweeping the whole ISM band to identify the new initialization position f_0, a more efficient strategy consists in widening the interrogation window around the last known value of f_0, under the assumption that the physical quantity is slowly varying with respect to the sampling rate and that f_0 has not significantly shifted. This flexibility in selecting the emitted frequency and including the computation of the next frequency comb is the result of the use of a DDS as the RF source under the control of a general purpose microcontroller.

5 Application

We experimentally assess the interrogation strategies described so far by probing a dual-resonance SAW sensor designed for temperature measurement in the range [0-160C].. The first order differential TCF of this dual

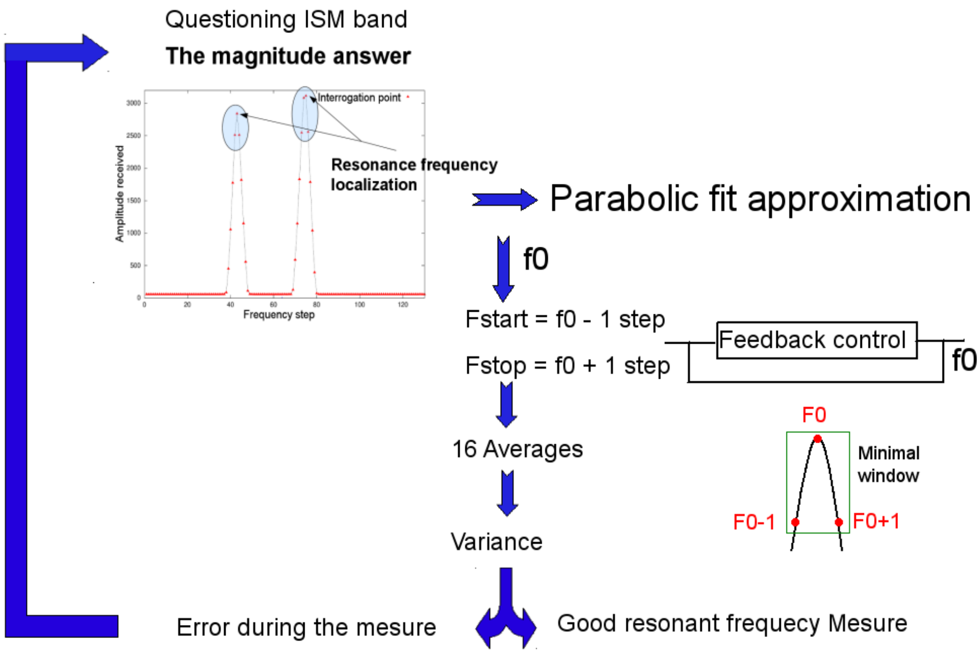

Figure 6: 3-point resonance frequency identification algorithm, with a feedback control of the emitted pulse frequencies on the previously identified resonance.

resonator sensor is 2500 Hz/K (6 ppm/K). The 2 interogation methods are compared in the case of a moving sensor, attached to a rotating wheel at 3000 rpm. Each mesurement is considered valid after accumulating 16 resonance frequency samples, allowing for an assessment of the data quality through the computation of the variance within these samples.

We have identified previously that the time needed to acquire each sample is $128 \times 60 = 7.7$ ms in the case of the fixed frequency comb strategy which always sweeps the ISM band using 128 samples, while the 3-point strategy only requires $2 \times 3 \times 60 = 360$ μs. Our ability to identify the resonance frequencies is defined by the antenna angular coverage: each resonance must be seen long enough for the measurement to be completed. The refresh rate is constant for the fixed comb strategy at 7 Hz including data transfer duration – an additional 11 ms every 16-samples for typical 60 character sentences transfered through the 57600 bauds asynchronous RS232 link. This sampling rate is increased to 174 Hz once the 3-point algorithm has been initialized, excluding the data communication duration.

The fast 3-point strategy either allows for an increased sampling rate or, for a given sampling rate, for the accumulation of more samples when computing the resonance frequency average. Futhermore, since the visibility duration of the sensor needed to perform the measurement is reduced by a factor 21, the rotation speed of the sensor can be increased by the same value considering a given antenna angular coverage. Typical applications include monitoring sensors on rotating equipment, with typical rotation speeds of 3000 rpm or 50 Hz. Based on the previous considerations, the angular coverage of the interrogation unit antenna must be 120^o in the former case, while it is reduced to a more reasonable 6^o, compatible with antennas of reduced dimensions as requested for monitoring industrial equipment.

In terms of measurement resolution, the algorithm has been characterized by interrogating a temperature sensor made of dual-SAW resonators, connected to the antenna output through a 25 dB attenuator simulating a fixed electromagnetic environment. The resulting Allan deviation plot (Fig. 7) exhibits a noise level of 100 Hz at the single sample level ($\tau = 5.76$ ms), reduced to 3 Hz when averaging 1000 points (sampling rate: 576 ms).

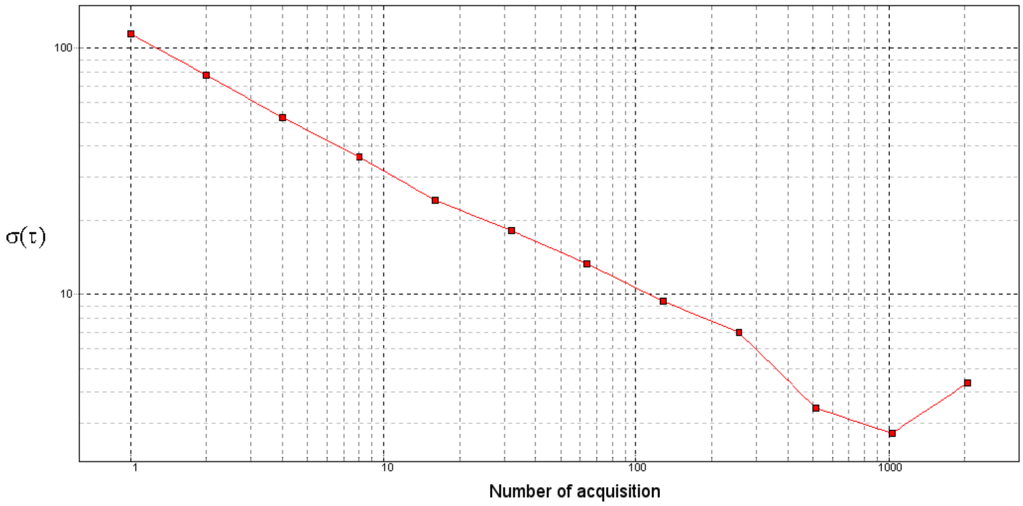

Figure 7: Allan deviation as a function of the samples included in the averaging window. The samples are separated by 5.76 ms.

6 Conclusion

We have demonstrated how to use a flexible radiofrequency generation system centered on a microprocessor-controlled direct digital synthesizer and a duplexer for switching between an emission phase and a reception phase for probing wireless passive acoustic resonators used for sensing purposes. We have demonstrated the improved performance of a feedback stategy requiring, once intialized, only three probe pulses to identify with sub-100 Hz resolution the resonance frequency of the devices operating in the 434 MHz ISM band.

Thanks to this strategy, the sensor only needs to be seen by the interrogation unit during 360 μs, with applications towards monitoring rotating equipment for preventive maintenance in industrial environments. Furthermore, the bias source associated with a second-order polynomial fit of the resonance shape is eliminated using this technique.

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