A stroboscopic approach to surface acoustic wave delay line interrogation

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***Abstract*—A pulsed RADAR approach is investigated to probe acoustic delay lines used as passive sensors. In order to comply with the requirements of compact, low power receiver electronics, a stroboscopic equivalent time sampling approach is demonstrated. A strategy for generating high resolution time delays while allowing for long interrogation durations (up to 5 μs) is implemented by combining an FPGA-based delay generator with commercially available programmable digital delay lines. The measurement sequence of generating interleaved combs is due to the long delay line reconfiguration duration (SPI communication) with respect to the coarse comb (FPGA based counter). The response of the sensor is recorded and processed to acquire the coarse acoustic velocity information through magnitude measurement, and an accurate physical quantity estimate is computed thanks to the phase information. We demonstrate an improved software measurement strategy which prevents the slow process associated with a stroboscopic approach and allows to reach refresh rates of up to 20 kHz when probing an acoustic tag for a physical property measurement, while keeping the hardware to a bare minimum.**

I. INTRODUCTION

Acoustic delay lines are well know transducers used as passive sensors interrogated through a wireless link. The inverse piezoelectric effect converts the energy of an incoming electromagnetic pulse, trough the interdigitated transducer (IDT) connected to the antenna, to an acoustic wave propagating on a piezoelectric substrate. Mirrors patterned on this substrate reflect a fraction of this wave back and the direct piezoelectric effect converts these acoustic pulses to electromagnetic signals detected by the receiver. The interrogation unit design is given by the characteristics of the sensor response. As part of this study, we will be interested in probing a commercially available acoustic delay line provided by the Carinthian Tech Research (CTR, Villach, Austria) whose spectral and time response is displayed in Fig. 1.

The delay line is probed with an excitation signal whose spectral characteristics lie in the 2.4 to 2.454 GHz range, hence complying with the industrial, scientific and medical (ISM) band regulations. The time-domain response of this line for a 54 MHz bandwidth excitation signal exhibits eight echoes between 994 ns and 2.19 μs. Two of these echoes partially overlap due to the reduced bandwidth, but are still separated by a gap exhibiting a 17 dB dynamic range.

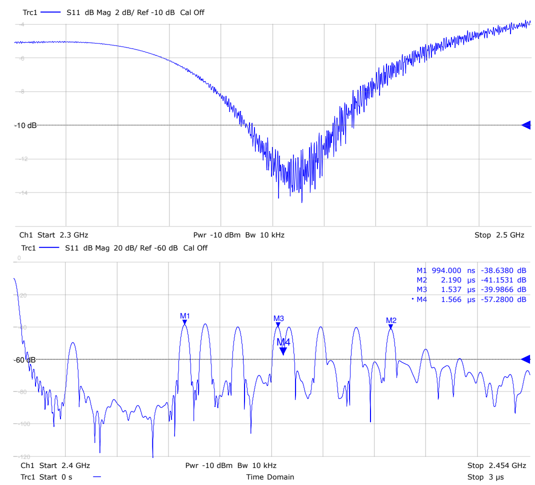

Figure 1. Top: S_{11} spectral response of a CTR delay line between 2.3 GHz and 2.5 GHz. Bottom: 3 μs time response with an excitation signal of 2.427 GHz and a bandwidth of 54 MHz. The 8 echoes are visible, with insertion losses of 40 dB, due to mirror efficiency, with an additional parasitic echo due to the back edge of the device at 350 ns after the excitation signal.

Multiple electronic reader units have been presented in the literature, most of which are based on the Frequency Modulated Continuous Waves (FMCW) RADAR approach [1], [2] whose control of the spectrum use and radiofrequency synthesis circuit is most basic, although requiring significant computational power (periodic audio-frequency rate sampling and Fourier transform) to extract the electrical properties of the acoustic delay line acting as cooperative target. Furthermore, FMCW requires a well linearized voltage controlled oscillator or linear digital synthesis for the Fourier transform components to coherently sum throughout the frequency excursion over the transfer function of the transducer [3], [4].

Another complementary approach is the pulsed RADAR method in which the frequency band, rather than being continuously swept, is probed by a wideband pulse. Echoes in the time domain are returned by reflectors following a delay proportional to their distance. In such a configuration, the challenge no longer lies in the signal source but on the wideband receiver whose sampling rate must be high with respect to the occupied bandwidth. One well known solution, best suited in the case of RADAR in which the environment is probed by a signal generated by the instrument and acting as a trigger signal, is the stroboscopic method as used for example in Ground Penetrating RADARs (GPR). Such an instrument has been demonstrated to be compatible with recovering the time domain response of acoustic transducers acting as passive cooperative targets [5], [6].

Before discussing the operation of the proposed reader unit, we first explain the reasons for choosing a pulsed RADAR approach rather than the classical FMCW RADAR method. Secondly, we explain the principle of equivalent time sampling and our system requirements. Details and implementation of this method are then discussed. Finally, measurements and results are reported with a discussion of the reader improved sampling rate.

II. Pulsed Radar

We assess the use of a pulsed RADAR approach in which the instantaneous power reaching the target is greatly increased with respect to a continuous emission, even though the average power consumption (depending on pulse repetition rate) is of the same order of magnitude than those found in FMCW. We assume that the emitted power must comply with ISM band regulations [7, Annex 1H] – 10 dBm emitted power in the 2.4 to 2.483 GHz ISM band – since common acoustic sensors do not occupy wide enough bandwidths to be considered as ultra-wideband devices.

Both FMCW and pulsed RADAR propagation characteristics are governed by the RADAR equation which will be used to assess the maximum interrogation range of acoustic transducers acting as cooperative targets. The one-way propagation equation relates the received power P_r to the instantaneously transmitted power P_t through

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi R)^2} \tag{1}$$

assuming that both the transceiver and the sensor are fitted with an antenna exhibiting a gain (G) equal to 1. λ is the signal wavelength and R the range between the RADAR and the sensor.

Once the sensor is loaded, the reflected power P_r' must account for the insertion loss IL of the device. We thus estimate the interrogation range R of a sensor by considering that the returned signal power S is given following

$$R = \frac{G \cdot \lambda}{4\pi} \sqrt[4]{\frac{P_t}{S \cdot IL}} \tag{2}$$

Hence, the range limitation is given by the P_t to S ratio and we consider S_{min} the minimum detectable power on the receiver defined as the minimum acceptable signal to noise ratio $(S/N)_{min}$ multiplied by the thermal noise injected into the low noise amplifier (LNA) $k_B T_0 BF$ with k_B the Boltzmann constant, T_0 the antenna and LNA temperature, B the receiver bandwidth and F the amplifier noise factor.

The relationship providing an estimate of the acoustic device interrogation range as a function of the instantaneously transmitted power is:

$$R_{max} = \frac{G \cdot \lambda}{4\pi} \sqrt[4]{\frac{P_t}{S_{min} \cdot IL}} \tag{3}$$

The receiver bandwidth defines the thermal noise level on the receiver and hence the detection limit: in the case of FMCW, typical sweep rates of the frequency source spanning 50 MHz is in the 10 ms range, yielding beat frequencies when probing an acoustic delay line with echoes delayed by up to 5 μs of $50 \times 10^6 \times 5.10^{-6}/10^{-2} = 25$ kHz. We will thus consider and FMCW recording bandwidth of 30 kHz, much lower than the pulsed RADAR receiver bandwidth of a few hundred MHz.

Assuming an FMCW system continuously transmitting 10 dBm and fitted with a receiver with 30 kHz bandwidth characterized by a noise figure of 3 dB, a signal to noise ratio of 3 dB and 40 dB of insertion losses in the acoustic device, then the maximum interrogation range is about 1.5 m. Such an interrogation range is achieved by instantaneously emitting 43 dBm (20 W or 32 V in a 50 Ω load) pulses by a pulsed RADAR setup designed with a receiver bandwidth of 54 MHz. For such a device to comply with ISM regulation and emit the same average power, the 20 ns long pulses must be emitted no faster than once every 34 μs. In this context, the pulsed RADAR refresh rate can reach 29.4 kHz. A tradeoff aimed at reducing the time interval between pulse emission is achieved by lowering peak power, at the cost of reduced range. In the next part, we will assume a pulse repetition rate interval of 5 μs (with a peak power of 34 dBm providing an interrogation range of 93 cm following the previous calculation).

The general pulsed-RADAR system architecture is shown in Fig. 2. A carrier frequency generated by a continuous source centered around 2450 MHz is chopped by a fast (<30 ns rise time) switch to load energy in an acoustic delay line. The returned echoes are translated to baseband by a wideband I/Q demodulator, feeding the dual-channel acquisition system which will be the topic of the next section.

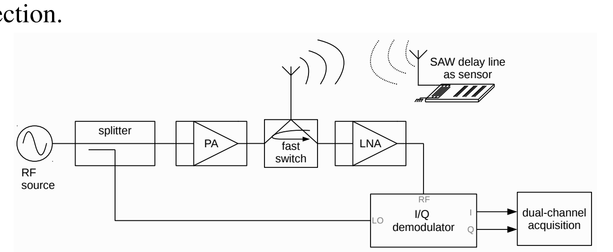

Figure 2. Schematic of a passive wireless acoustic sensor interrogation unit

In order to comply with the requirements of compact, low power receiver electronics, a stroboscopic equivalent time sampling approach is used. The two values representative of the physical quantity detection by the transducer are the returned power magnitude and phase, as provided by an I/Q demodulator. This demodulator provides an output signal of up to 100 MHz bandwidth, which involves digitizing a signal at 200-1000 MSamples/s to obtain a sufficient number of points to extract magnitude and phase with the targeted resolution aimed at only being limited by the local oscillator phase noise. The equivalent-time sampling approach provides a trade-off between reducing the demand for fast electronics components and increasing the acquisition time.

III. Equivalent Time Sampling

Equivalent time sampling (ETS) is based on repeating the probe signal and recording at each iteration a single sample at various time delays with respect to the emitted pulse. This measurement strategy is best suited when actively probing the medium, as done in RADAR systems, since the emitted pulse acts as a synchronization trigger to define the recording time delay.

Considering the time reference, common to all measurements, defined as T_0, then at each iteration the ETS system record a sample at $T_0 + n \cdot \delta T$ with sample index $n \in [1 : N]$, N being the number of samples in the reconstructed signal. The time step δT yields an equivalent sampling rate $f_s = 1/\delta T$. The two main disadvantages of this technique are the duration of the acquisition which depends on the number of samples and the repetition rate since N individual measurements are needed, and the need for a reproducible signal during the N measurements. These drawbacks are considered here to be overcome by the simple hardware setup made solely of a fast track and hold controlled by a programmable delay line while only low bandwidth analog to digital converter and memory access are needed otherwise.

In order to perform post-processing calculation on echoes characterization with at least 10 samples during each echo lasting about 10 ns, a sampling rate of at least 1 GS/s is targeted. Commercially available programmable delay lines suiting our needs exhibit delay resolutions between 1 ns and 100 ps. Acquisition of a time response between 500 ns and 5 μs at a rate of 1 GS/s involves 4,500 measurements. When acquiring one measurement point, it is necessary to wait 5 μs to avoid temporal aliasing and allowing for all returned signal from the acoustic sensor to fade out: hence yielding an incompressible measurement duration between 22.5 ms. Obtaining the same result while complying with ISM regulations requiring repetition rates no faster than 34 μs yields an acquisition time of at least 153 ms.

IV. Experimental setup

The challenge in using such commercially available delay lines is the range of accessible delays: an 8-bit programmable delay line such as Maxim DS1023-25 providing a resolution of 250 ps only generates a maximum delay of $2^8 \cdot 250$ ps $= 63.75$ ns, much below the targeted 5 μs. Two delay lines are thus cascaded, one for coarse delay generation and another for high resolution delay generation. The coarse delay line must exhibit low jitter (necessarily less than the accurate line delay, in this case 250 ps): in our case, the delay generator is provided by a Programmable Logic Device (PLD) clocked at 100 MHz which ensures a time resolution of 10 ns. This device also generates the trigger signal of the switch.

The duration for programming a Maxim DS1023-25 delay line through a SPI link is also taken into account for the total measurement time estimate. Although the fastest clock rate on the SPI bus is 10 MHz, we secure communication by clocking the bus at 1 MHz. For each measurement, the delay line must be programmed by an 8-bit word, so the programming duration 8 μs. In addition, some latencies is associated with the delay line programming, requiring an additional 530 ns, and measurements can only be repeated after the acoustic sensor response has faded out after 5 μs. Thus, the total duration for a 4,500 point dataset is $4500 \times (8 + 0.53 + 5 + 0.02) = 60975$ μs $\simeq 61$ ms. Fortunately, thanks to an optimized scanning strategy of the response, it is possible to reduce the programming time.

Considering a 10 ns resolution coarse delay, and a 1 ns fine delay equal to 4-delay line steps, 10 measurements are needed between two coarse delays to achieve a 1 GS/s sampling rate. The programming time of a PLD is at most two periods of the core clock. Rather than continuously reprogramming the slow (SPI bus) fine delay, an optimized approach consists in setting the fine delay and sweeping the coarse delay over the whole acoustic sensor response range (0 to 5 μs). Having acquired this first dataset, the fine delay line is set again (requiring a 8.53 μs lag) and the system retrieves a second dataset. The operation is repeated 10 times to get the full response. This stroboscopic acquisition using interleaved coarse and fine delay combs (Fig. 3) allows a theoretical acquisition time of 22.7 ms in the same conditions of the previous calculation, or a threefold update rate improvement with respect to the basic strategy described above.

So far no assumption is made on the acoustic sensor echo position. However, once the measurement has been performed, a strong assumption is that the echoes will be located close to their last identified position. Hence, rather than scanning the whole acoustic sensor delay of 0.5 to 5 μs by 1 ns steps, we focus solely on a feedback loop approach requiring 3-measurements on each echo. The central delay is then computed using a parabolic fit and feeds the next measurement step. The total measurement duration is then reduced by limiting from 4,500 to $3 \times 8 = 24$ samples for an acoustic sensor encoding 8 bits. The associated measurement duration is $24 \times (8 + 0.53 + 5 + 0.02) = 325.2$ μs. If furthermore only the central delay needs fine tuning and the two other measurements before and after the central delay only require reprogramming the coarse delay (10 ns steps), then the measurement duration is further reduced to $8\times(8+0.53+5+0.02)+16\times(5.02) = 189$ μs or a 5.3 kHz refresh rate.

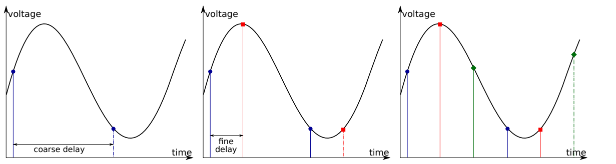

Figure 3. Example of a sine-wave reconstruction with stroboscopic acquisition interleaving coarse and fine delay combs. Each case represents a coarse comb of recorded samples. The transition from one case to another requires setting the fine delay line.

V. Results

This acquisition system scans the output of the I/Q demodulator to calculate the physical quantity to be measured in a post-processing step. Fig. 4 shows the I and Q data recorded from 500 ns to 3 μs and the resulting $|I+iQ|$ magnitude, favorably compared to the measurement performed using a network analyzer (Fig. 1).

Beyond the acoustic tag identification based on the magnitude calculation, extracting a velocity information associated with a physical quantity measurement is achieved by computing $\arg(I+iQ)$. A differential measurement only requires the estimate of the phase difference between two echoes: only two acquisition points of both I and Q signals with a dual analog-to-digital converter are needed. Using the afore mentioned 3-point strategy for each echo, only 6 measurements are performed requiring a total measurement duration of $2\times(8+0.53+5+0.02)+4\times(5.02) = 47$ μs. Circles on Fig. 4 display the delay at which these 6 measurements are performed in order to characterize the first two echoes in the context of a temperature measurement, thus providing a refresh rate of about 20 kHz. While such an update rate is still 10 times lower than the maximum achievable measurement speed of a 5 μs delay acoustic sensor, it optimizes an embedded electronics approach requiring only a few high-bandwidth components (track and hold, switch, I/Q demodulator).

VI. Conclusion

A pulsed mode RADAR optimized for minimizing the number of high-bandwidth components and fast sampling rate is demonstrating for probing wideband acoustic transducers acting as passive wireless sensors. Compliance with ISM regulation and reaching the same range than an FMCW approach nevertheless allow a pulsed RADAR approach to improve at least 10-fold the refresh rate assuming a wideband receiver (fast radiofrequency analog to digital converter).

A stroboscopic strategy reducing the number of wideband components to a switch, a fast track and hold and

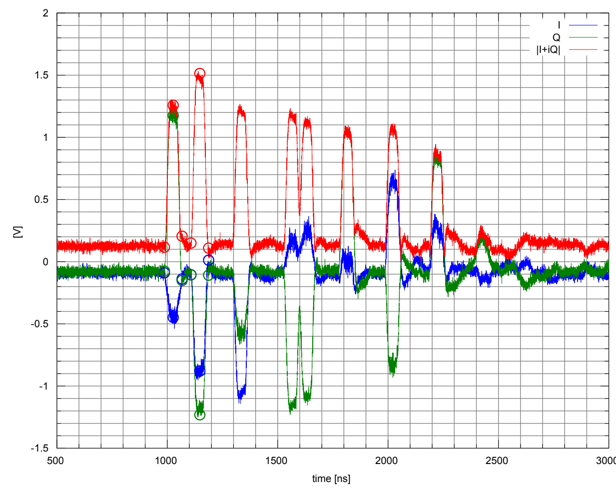

Figure 4. Acoustic delay line response sampled by a stroboscopic interrogation unit. Six circles are highlighted on each trace over the first two echoes, representing the minimum number of samples recorded for a temperature measurement.

I/Q demodulator associated with an optimized algorithm of interleaved coarse and fine time delays provides tag identification at 5.3 kHz refresh rate while measuring a physical quantity using acoustic phase computation on two echoes is performed at 20 kHz.

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