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Correspondence

Estimator for Reflective Delay Line-Type SAW Sensors

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***Abstract*—This correspondence presents an estimator for reflective delay line-type surface acoustic wave (SAW) sensors. The estimator is derived from an analytical model and its range of validity is discussed. The proposed estimator enables simultaneous access to several SAW sensors with time-orthogonal responses and it can be implemented in a computationally efficient way utilizing the fast Fourier transform algorithm. The estimator is experimentally verified and its performance is compared with that of a reference estimator.**

I. Introduction

Wireless sensors offer a great potential in several applications for which the use of wired sensors is not cost-effective or at all possible. Surface acoustic wave (SAW) tags [1] offer a great potential in sensor applications: SAW components can be tailored to be sensitive to several environmental variables, they do not require an external sensor element (although it is possible to use such an element [2]), they can be accessed wirelessly and they do not require a battery, the use of which might limit the sensor lifetime and operation conditions, such as temperature. In addition, SAW sensors can be used in harsh environments and they are relatively small and inexpensive. SAW sensors are reviewed for example in [1], [3]–[6]. SAW sensors have been reported to monitor e.g., temperature [7], pressure [7], [8], torque [9], and bending [8].

SAW components transform electromagnetic energy into acoustic waves propagating on the surface of a piezoelectric substrate. Reflective delay line (RDL)-type SAW tags have acoustical reflectors on the surface of the substrate, producing delayed reflections of the pulse that is used to interrogate the tag. The ID of the tag is coded in its temporal response, i.e., the reflector placement.

The ID code of the tag is resolved either by directly measuring its time response with a pulsed signal or performing the measurements in frequency domain (FMCW interrogation) and reconstructing the time response with a Fourier transform. In sensor applications, the scaling of the time response is of interest as it is directly related to the measured quantity. Several estimators have been reported for interrogating SAW sensors.

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A method for maximizing the signal-to-interference ratio in FMCW interrogation is presented in [10]. In this method, the frequency window function is optimized (or matched) for a given tag with a specific time response. This method may slow down the interrogation speed because of the computational load of window optimization. However, it is found sufficient to optimize the window only once, during the first interrogation, thereby delaying only the first interrogation.

A correlative signal processing method for estimating the relative time delay of a SAW tag is presented in [11]. In this method, the measured time response of the tag under sensor effect is correlated with the time-scaled responses of the same tag at a known sensor state (e.g., at known temperature). In the paper, the correlation procedure is implemented with hardware, which enables high-speed interrogation. However, software implementation of the correlation procedure may be very slow.

An FMCW interrogation method for RDL-type SAW sensors is described in [12]. The method utilizes the intersymbol interference between different reflections, which are caused by the long duration of the interrogation pulse. Because of the long pulse duration, the method uses only a narrow bandwidth. A drawback is a decrease in interrogation speed.

In this correspondence, we present an estimator for solving the scaling of time response of an RDL-type SAW sensor. This correspondence is organized as follows: Section II derives the estimator from an analytical model, Section III shows experimental results, and Section IV concludes the paper.

II. Theory

A. RDL-Type SAW Sensor

A wireless RDL-type SAW sensor (see Fig. 1) receives an interrogation pulse with an antenna. The electromagnetic pulse is transformed into SAW with an interdigital transducer (IDT) placed on piezoelectric material [13]. The reflectors on the substrate reflect the interrogation pulse back to the IDT, which again converts the SAW into electrical signal. This response signal consisting of delayed reflections is then transmitted back to the interrogation unit.

An impulse response of an RDL-type SAW tag or sensor is given as

$$h(t) = h_{\mathrm{ea}}(t) \otimes \sum_{i=1}^{N} a_i \delta(t - T_i), \quad (1)$$

where $h_{\mathrm{ea}}(t)$ is the combined electro acoustic impulse response of the IDT and a reflector, a_i is the reflection coeffi-

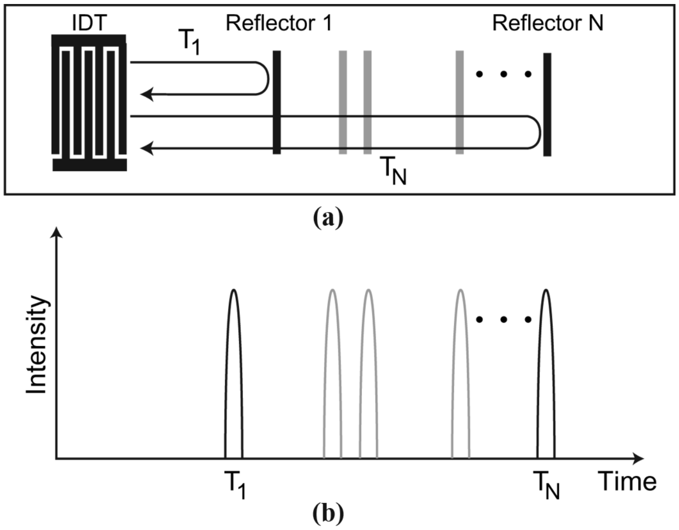

Fig. 1. A schematic layout of reflective delay line surface acoustic wave sensor (a) and the corresponding impulse response of the sensor (b). IDT = interdigital transducer.

cient of the ith reflector, $\delta(t)$ is the Dirac's delta function, N is the number of reflectors, and T_i is the time delay of the ith reflection. The time delay is given as $T_i = 2L_i/v$, where v is the acoustic velocity and L_i is the one-way path length to the ith reflector. In the following analysis, the electro acoustic impulse response $h_{\mathrm{ea}}(t)$ is assumed to be much narrower in time than the duration of the interrogation pulse, and it is therefore neglected.

In RDL-type SAW sensors, a change of Δx in the measured quantity x, such as temperature, changes both the acoustic path length and SAW velocity. As a consequence, $h(t)$ is scaled in time and the impulse response of the SAW sensor (1) under sensor effect can be written as

$$h(t,\Delta x) = \sum_{i=1}^{N} a_i \delta(t(1+\varepsilon\Delta x) - T_i), \tag{2}$$

where the parameter ε expresses the relation between the relative time delay and a certain change in the measured quantity.

B. Estimator for Relative Time Delay Difference

The interrogated response of the SAW sensor is a convolution with the impulse response in (2) and the interrogation pulse $w(t)$:

$$y(t,\Delta x) = w(t) \otimes h(t,\Delta x). \tag{3}$$

The wireless propagation path causes both attenuation and delay to the measured impulse response. For simplicity, both phenomena are neglected in the following analysis. The attenuation will not affect the estimator, as will be seen later, and the delay caused by the interrogation distance can be solved if necessary; for example, convolving the measured impulse response of the tag with a known reference response.

When considering the FMCW interrogation, the time domain interrogation signal that is obtained by taking the Fourier transform of the FMCW frequency window, is given as (note that this signal differs from the actual time domain FMCW signal)

$$w(t) = e^{-j2\pi f_c t} w_s(t), \tag{4}$$

where f_c is the center frequency of the frequency window, and $w_s(t)$ is the time response of the FMCW frequency window shifted to zero frequency. Substituting (4) and (2) into (3) gives

$$\begin{aligned} y(t,\Delta x) &= e^{-j2\pi f_c t} w_s(t) \otimes \sum_{i=1}^{N} a_i \delta(t(1+\varepsilon\Delta x) - T_i) \\ &= \sum_{i=1}^{N} a_i e^{-j2\pi f_c (t(1+\varepsilon\Delta x) - T_i)} w_s(t(1+\varepsilon\Delta x) - T_i). \end{aligned} \tag{5}$$

Let us assume that

$$\int_{-\infty}^{\infty} \left| w_s(t(1+\varepsilon\Delta x) - T_n)\right| \left| w_s(t(1+\varepsilon\Delta x) - T_m)\right| dt = 0, \quad n \neq m, \tag{6}$$

i.e., the temporal separation between the reflectors is greater than the duration of the interrogation signal. (Violating this assumption may decrease the accuracy of the estimator.) Then

$$\begin{aligned} y(t,\Delta x) y^*(t,\Delta x = c) = \sum_{i=1}^{N} \left| a_i \right|^2 e^{-j2\pi f_c t \varepsilon (\Delta x - c)} \\ \times w_s(t(1+\varepsilon\Delta x) - T_i) w_s^*(t(1+\varepsilon c) - T_i), \end{aligned} \tag{7}$$

where $y(t,\Delta x = c)$ is the measured sensor response when the measurand $\Delta x = c$ is known, later called the reference time response, and * denotes the complex conjugate. Let us assume that $(T_N - T_1)\varepsilon(\Delta x - c)$ is small compared with the duration of $w(t)$. Then (7) can be written as

$$\begin{aligned} y(t,\Delta x) y^*(t,\Delta x = c) = e^{-j2\pi f_c t \varepsilon (\Delta x - c)} \\ \times \sum_{i=1}^{N} \left| a_i \right|^2 \left| w_s(t(1+\varepsilon\Delta x) - T_i) \right|^2. \end{aligned} \tag{8}$$

Multiplying both sides of (8) by $y(t,\Delta x = c) y^*(t,\Delta x = c)$ and taking the Fourier-transform gives

$$\begin{aligned} F\left\{ y(t) y^*(t,\Delta x = c) y(t,\Delta x = c) y^*(t,\Delta x = c) \right\} = \\ \delta(f - f_c \varepsilon(\Delta x - c)) \otimes F\left\{ \sum_{i=1}^{N} \left| a_i \right|^2 \left| w_s(t(1+\varepsilon\Delta x) - T_i) \right|^2 \right\} \\ \otimes F\left\{ \sum_{i=1}^{N} \left| a_i \right|^2 \left| w_s(t(1+\varepsilon\Delta x) - T_i) \right|^2 \right\}. \end{aligned} \tag{9}$$

The first term $\delta(f - f_c\varepsilon(\Delta x - c))$ represents Dirac's delta function at the frequency $f = f_c\varepsilon(\Delta x - c)$. This peak is convolved 2 times with the spectrum of the autocorrelation function of the reference time response. The autocorrelation function of the reference time response is real and therefore its spectrum is conjugate symmetric. The maximum of a self convolution of a conjugate symmetric function occurs at zero and therefore the measured quantity is found from

$$\Delta x = \frac{f'}{\varepsilon f_c} + c, \tag{10}$$

where f' maximizes

$$\max_f \left\{ \left| F\left\{ y(t,\Delta x) y^*(t,\Delta x = c) y(t,\Delta x = c) y^*(t,\Delta x = c) \right\} \right| \right\}. \tag{11}$$

Eq. (11) can be solved by simply taking the Fourier transform and finding the maximum or utilizing other techniques, such as the MUSIC algorithm [14]. The Fourier transform approach enables computationally efficient implementation using the fast Fourier transform (FFT) algorithm. In addition, when using FMCW interrogation, the time response $y(t)$ can be solved with FFT.

The proposed estimator enables simultaneous access to multiple sensors having time-orthogonal responses as the product $y(t,\Delta x)y^*(t,\Delta x = c)$ in (11) is zero if these 2 responses are time-orthogonal.

C. Limitations to the Method

There are some limitations to the proposed method. First, the spectrum of the autocorrelation function of the time response is a periodic function. Therefore, convolving it with the shifted spectrum of the autocorrelation function produces maxima which are separated by the period of the spectrum. In general, the spectrum of a periodic function with a period of T contains peaks at frequencies $f = n/T$, where n is an integer. Therefore, this estimator is valid when $-1/T < f' < 1/T$, where T is the time delay between the reflectors. However, in practice the reflector separation is usually not constant, in which case the practical range of validity can be derived from the spectrum of the autocorrelation function.

In the proposed estimator, the measured time response is multiplied with a known time response of the sensor. If the relative time scaling between these 2 is too large, they do not match perfectly and therefore some of the signal energy is lost. To ensure that all N reflections are contributing to the estimator, it is required that the ith reflections in both time responses $y(t,\Delta x)$ and $y(t,\Delta x = c)$ overlap. This requirement is satisfied when

$$\left|\varepsilon(\Delta x - c)\right| < \frac{\tau_{\text{pulse}}}{2(T_N - T_1)}, \tag{12}$$

where τ_{pulse} is the duration of $w_s(t)$ and $T_N - T_1$ is the time delay between the first and the last reflector. For example, the pulse length is approximately 25 ns for a uniformly weighted 40 MHz frequency window. Considering a SAW sensor with 2 μs time delay difference between the first and the last reflector, the absolute value of the relative time scaling $|\varepsilon(\Delta x - c)|$ should not exceed 6.25‰.

III. Experiments

A. Experimental Setup

The proposed method is experimentally verified by measuring the temperature response of an RDL-type lithium niobate ($LiNbO_3$) SAW tag operating at 2.45 GHz. The tag was attached to an aluminum block with a reference thermocouple temperature sensor (Prema 3040, National Instruments, Austin, TX). The aluminum block was first cooled down to 0°C and then heated up to 55°C with a power resistor.

The tag was interrogated by measuring its frequency response with a network analyzer (Agilent 5230A, Agilent Technologies, Santa Clara, CA) from 2.43 GHz to 2.47 GHz in 201 discrete frequency points (200 kHz frequency interval with 40 MHz bandwidth).

B. Reference Estimator

The performance of the proposed method is compared with a conventional method in which the time delays are directly obtained from the measured time response (or Fourier transform of the measured frequency response in case of FMCW interrogation) [15]. In this reference method, the time delay differences between ith and the first reflectors $T_{1,i}$ are calculated from

$$T_{1,i} = T_i - T_1 - \angle\left(\frac{y(T_i)}{y(T_1)}\right)\frac{1}{4\pi f_c}, \tag{13}$$

where T_i are the temporal points of local maxima of $|y(t)|$ corresponding to ith reflections, $\angle$ gives the angle of complex number, and f_c is the center frequency of the interrogation signal. The estimator first locates the reflections roughly using the amplitude response and then calculates more accurate estimations for the reflection delays taking the phase information into account. The time delay coefficient is then solved as

$$\min_{(1+\varepsilon\Delta x)} \left\{ \sum_{i=2}^{N} \left| \frac{(1+\varepsilon\Delta x)T_{1,i}}{T_{1,i,\Delta x=c}} - 1 \right|^2 \right\}, \tag{14}$$

where $T_{1,i,\Delta x=c}$ are the time delay differences between reflections at $\Delta x = c$.

C. Experimental Results

The measured time response of the tag at 25°C is shown in Fig. 2. This response was used as the known re-

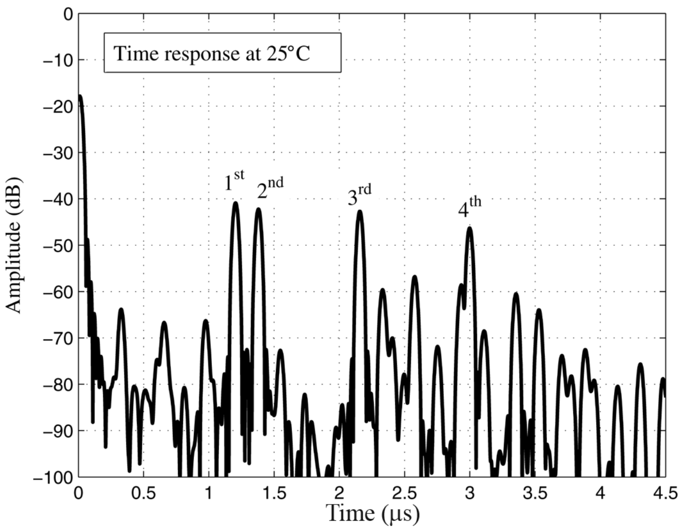

Fig. 2. The time response of the tag at 25°C. The tag has 4 reflectors with corresponding delays of 1.20, 1.38, 2.16, and 3.00 μs.

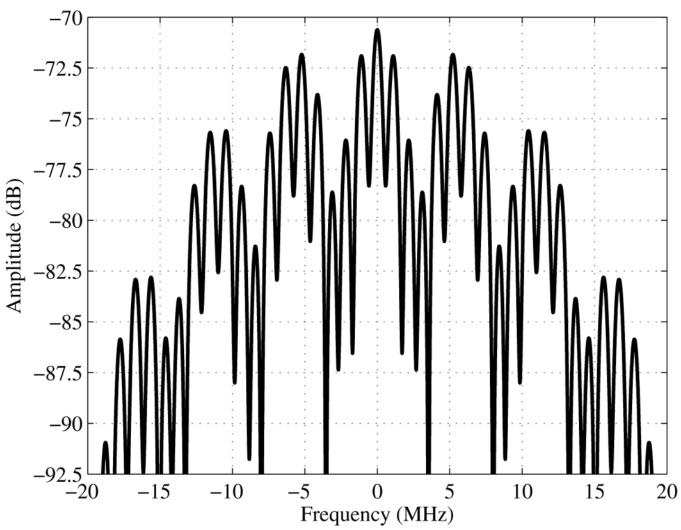

Fig. 3. The autocorrelation spectrum of the sensor time response at 25°C.

sponse $y(t,\Delta x = 25°\text{C})$ when calculating the temperature responses.

The time response of the tag shows that there are 4 reflectors producing time delays of 1.20, 1.38, 2.16, and 3.00 μs. The spectrum of the autocorrelation function of the impulse response at 25°C (Fig. 2) is shown in Fig. 3.

The spectrum has high peaks at ± 5.22 MHz. These peaks correspond to the time delay difference between the first and the second reflector $[(T_2 - T_1)^{-1} = 5.56 \text{ MHz}]$. Because of these peaks, the range of validity of the estimator is $|f'| < 5.56/2 = 2.78$ MHz, or $|\varepsilon(\Delta x - c)| <$ 2.78 MHz/2.45 GHz = 1.15‰. The temperature response of the proposed estimator with the reference estimator is shown in Fig. 4.

The proposed estimator has very linear temperature response in the temperature range from 8°C to 42°C as compared with the reference estimator response, which has strong ripple and is clearly non-linear. The periodic ripple in the reference estimator response is most likely caused by intersymbol interference.

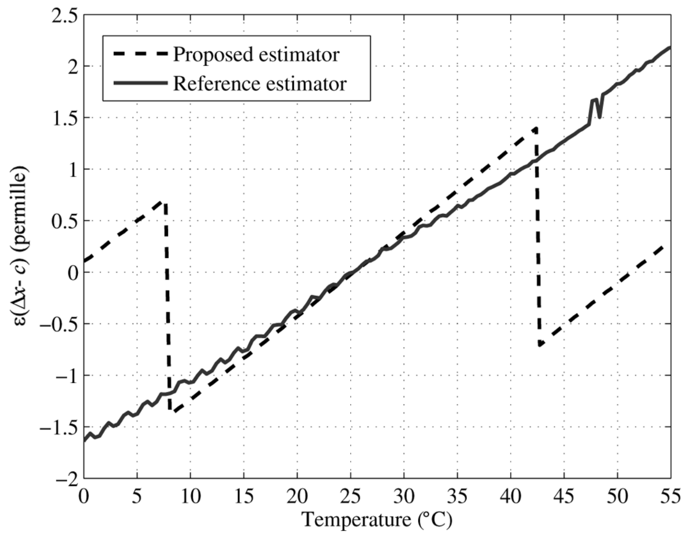

Fig. 4. The temperature response of the proposed estimator (dashed) and the reference estimator (solid).

The valid range of the proposed estimator is found to be $|\varepsilon(\Delta x - c)| < 1.38$‰, which slightly exceeds the assumed range of validity of 1.15‰. When the valid range is exceeded at 8°C and 42°C, the estimator has a discontinuity of 2‰ units, which equals the period of the spectrum of the autocorrelation function (5.22 MHz/2.45 GHz = 2‰). A line fit to the response of the proposed estimator in the temperature range from 8°C to 42°C gives the temperature coefficient of delay (TCD) of 81 ppm/°C at 25°C.

The frequency response of the SAW sensor was measured with a cable and therefore the signal-to-noise ratio (SNR) in the experimental data is very high. The standard deviations with both estimators at different SNRs were studied by adding white noise to the experimental data. The standard deviations of both estimators are shown in Fig. 5. The standard deviation is calculated from the difference between the estimators' responses and a line fit in the temperature range from 8°C to 42°C.

The proposed estimator tolerates some 20 dB lower signal-to-noise ratio than the reference estimator. Therefore, as the free-space loss in the 2-way radio path is proportional to the fourth power of the distance, the proposed estimator offers an interrogation distance 3 times longer than the reference estimator. In addition, the accuracy of the reference estimator at high SNRs is most likely limited by the intersymbol interference. As seen in Fig. 5, the proposed estimator achieves much better accuracy at high SNR levels.

The performance enhancement of the proposed estimator is based on the utilization of the known delay-line properties of the SAW tag. Note that the proposed estimator utilizes the complete reference response in (11), whereas the reference estimator only takes the delays between different reflectors into account in (14).

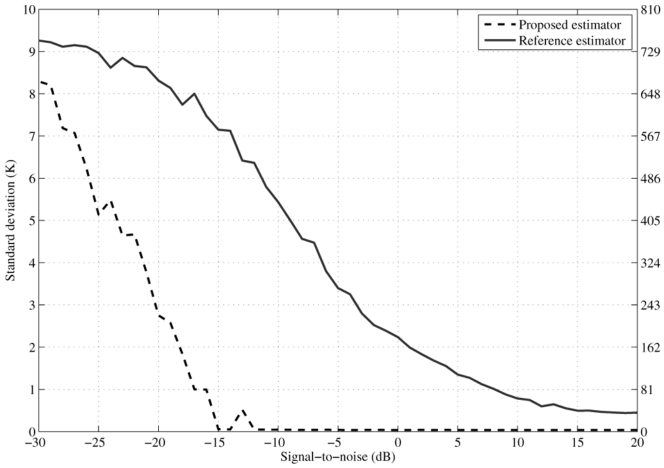

Fig. 5. The standard deviation with both estimators at different signal-to-noise ratios.

IV. Conclusion

In this correspondence, we have proposed an estimator for calculating the relative time delay (compared with the known time response) of an RDL-type SAW sensor. The estimator is derived from an analytical model, and its limitations are discussed. The estimator enables simultaneous access to multiple sensors with time-orthogonal responses and it can be implemented in a computationally efficient way using the FFT algorithm.

The estimator is experimentally verified and its performance is compared with that of a reference estimator. The valid range of the proposed estimator is found to be narrower than that of the reference estimator. However, as compared with the reference estimator, the proposed estimator is found to tolerate approximately 20 dB lower SNR in the valid range. In addition, the proposed estimator is found to tolerate intersymbol interference better than the reference estimator.

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