Title	Optimized signal processing for FMCW interrogated reflective delay line-type SAW sensors
Author(s)	Viikari, Ville; Kokkonen, Kimmo; Meltaus, Johanna
Citation	IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control vol. 55(2008):11, pp. 2522- 2526
Date	2008
URL	http://dx.doi.org/10.1109/TUFFC.961
Rights	Copyright © [2008] IEEE. Reprinted from IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control vol. 55(2008):11, pp. 2522- 2526. This material is posted here with permission of the IEEE. Such permission of the IEEE does not in any way imply IEEE endorsement of any of VTT Technical Research Centre of Finland's products or services. Internal or personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution must be obtained from the IEEE by writing to pubs-permissions@ieee.org. By choosing to view this document, you agree to all provisions of the copyright laws protecting it.

Correspondence

Optimized Signal Processing for FMCW Interrogated Reflective Delay Line-Type SAW Sensors

Ville Viikari, Kimmo Kokkonen, and Johanna Meltaus

***Abstract*—This correspondence presents an optimized frequency modulated continuous-wave (FMCW) interrogation procedure for reflective delay line-type SAW sensors. In this method, the time delays between reflections are obtained with Fourier transform from optimally windowed frequency response. Optimal window functions maximize the signal-to-interference ratio at chosen temporal points of interest. The method is experimentally verified and its accuracy is compared with that of a Fourier transform from Hamming-windowed frequency response.**

I. Introduction

In surface acoustic wave (SAW) components, the piezoelectric effect enables the transformation of electromagnetic energy into an acoustic wave, typically using an interdigital transducer (IDT) [1]. The IDT consists of interleaved metal electrodes patterned onto the surface of a piezoelectric crystal.

SAW components are widely used in telecommunications industry, because they enable the realization of signal processing functions such as filtering and pulse compression with considerably smaller required area than conventional electromagnetic components.

SAW components have also shown great potential as radio frequency identification (RFID) tags [2] and sensors. Compared with passive integrated circuit (IC) based RFID tags, reflective delay line (RDL) type SAW tags offer a longer interrogation distance and they are potentially more robust against environmental reflections in wireless interrogation. Active and semi-passive IC-based tags offer interrogation distance comparable to that of SAW tags, but they require a battery that increases the cost of the tag and limits its lifetime. Furthermore, SAW tags lend themselves well to use as sensors. They are relatively small, they do not require a battery, they can be interrogated wirelessly, and they can be tailored to be sensitive to several different measurands, such as temperature, strain, or pressure. In addition, wireless SAW sensors can be used with external sensor elements [3]. Extensive reviews of SAW tags and sensors can be found, for example, in [2], [4]–[7]. SAW sensors have been used to measure temperature [8], pressure [8], [9], torque [10], and bending [9].

Wireless SAW tags and sensors are interrogated with a pulsed signal or with a frequency modulated continuous-wave (FMCW) signal. In pulsed interrogation, a short pulse is transmitted and then reflections are recorded in the time domain. Pulsed interrogation is potentially faster than FMCW interrogation. However, this theoretically short interrogation time is usually increased by the need to average several pulses to obtain sufficient accuracy. Contrary to the pulsed interrogation, the frequency is swept over a certain bandwidth (BW) in FMCW interrogation. The impulse (time) response is calculated from the frequency response with Fourier transform. The advantages of the FMCW interrogation over pulsed interrogation are the potentially wider dynamic range and the more efficient utilization of the typically limited BW available. In addition, because a pulsed signal is not required, the signal power remains low, facilitating the circuit design of the interrogation unit. However, FMCW interrogation may be slower than pulsed interrogation because each discrete frequency point needs to be measured separately.

When interrogating a SAW tag or sensor, the time resolution should be better than the cycle duration at the center frequency of the interrogation signal. Achievable time resolution depends on the BW available: a larger BW yields a better time resolution. Time resolution may be limited by frequency regulations. For example, according to [11], it is challenging to obtain a sufficient time resolution at the 434 MHz industrial, scientific, and medical (ISM) band. The BW may also be further limited by the tag antenna. The fundamental BW of an electrically small antenna is limited by its electrical size [12]: the smaller the antenna in wavelengths, the smaller the achievable BW. Therefore, the antenna may also limit the miniaturization of the SAW tag or sensor.

In this correspondence, we propose a technique that can be used to improve the performance of FMCW interrogation scheme with a limited available BW. The technique enhances interrogation accuracy and improves BW efficiency. Bandwidth reduction decreases the interrogation time because it lowers the number of required discrete interrogation frequency points.

II. Theory

A. Reflective Delay Line-Type SAW Sensor

A wireless SAW sensor (see Fig. 1) receives the interrogation signal with an antenna. The electrical interrogation signal is then converted into a SAW with an IDT. Acoustical reflectors deposited on the substrate reflect back the

Manuscript received April 15, 2008; accepted June 8, 2008.

V. Viikari and J. Meltaus are with the VTT Technical Research Centre of Finland, Espoo, Finland (e-mail: ville.viikari@vtt.fi).

K. Kokkonen is with the Helsinki University of Technology (TKK), Espoo, Finland.

Digital Object Identifier 10.1109/TUFFC.961

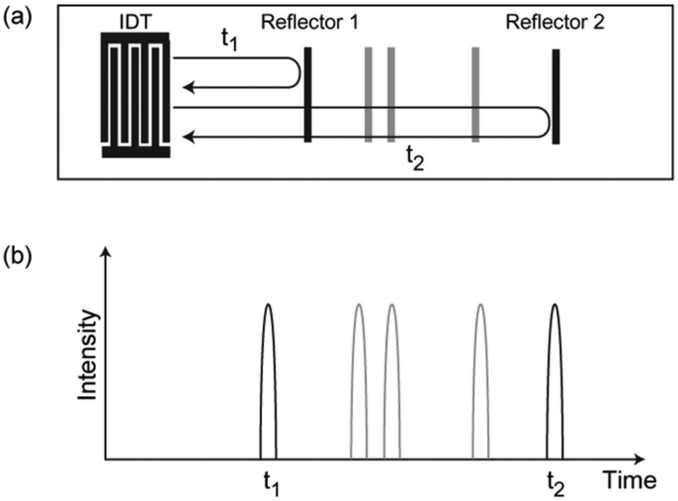

Fig. 1. (a) A schematic layout of a reflective delay-line type SAW tag. (b) Schematic impulse response of the tag. A change in, e.g., SAW propagation velocity affects the times t_1 and t_2 enabling a sensor with a differential readout.

acoustic waves, which are again converted into an electrical signal by the IDT structure. This response signal is then radiated by the antenna and propagated back to the interrogation unit.

Acoustical properties of a SAW substrate material are sensitive to surrounding conditions, such as temperature or strain. A change in the acoustic properties of the substrate affects the propagation of the SAWs. Therefore RDL-type SAW tags can be used as sensors by measuring the time delay difference between different reflections.

B. FMCW Interrogation

In FMCW interrogation, the interrogation frequency is swept across the available BW. The impulse (time) response is then calculated from the measured discrete frequency response as

$$s_{11}(t) = F^{-1}\{S_{11}(f) \cdot W(f)\}, \tag{1}$$

or in discrete form as

$$\begin{gathered}
\mathbf{s}_{11} = \mathbf{A}(\mathbf{S}_{11} \cdot \mathbf{W}), \\
\mathbf{s}_{11} = \begin{bmatrix} s_{11}(t_1) \\ s_{11}(t_2) \\ \vdots \\ s_{11}(t_M) \end{bmatrix}, \quad \mathbf{S}_{11} = \begin{bmatrix} S_{11}(f_1) \\ S_{11}(f_2) \\ \vdots \\ S_{11}(f_N) \end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix} W(f_1) \\ W(f_2) \\ \vdots \\ W(f_N) \end{bmatrix}, \\
\mathbf{A} = \begin{bmatrix} e^{j2\pi f_1 t_1} & e^{j2\pi f_2 t_1} & \cdot & e^{j2\pi f_N t_1} \\ e^{j2\pi f_1 t_2} & e^{j2\pi f_2 t_2} & & \cdot \\ \cdot & & & \cdot \\ e^{j2\pi f_1 t_M} & \cdot & \cdot & e^{j2\pi f_N t_M} \end{bmatrix},
\end{gathered} \tag{2}$$

where F^{-1} represents the inverse Fourier transform, $S_{11}(f)$ is the measured frequency response and $W(f)$ is the window function. Eq. (1) can also be expressed as

$$s_{11}(t) = F^{-1}\{S_{11}(f)\} \otimes F^{-1}\{W(f)\}, \tag{3}$$

where $\otimes$ denotes convolution. The term $s_{11}(t)$ can be understood as the impulse response obtained with the interrogation, the term $F^{-1}\{S_{11}(f)\}$ represents the fundamental impulse response, and the last term $F^{-1}\{W(f)\}$ is the temporal sampling function in the convolution integral. Ideally, the sampling function is the delta function, i.e., it selects one differential point of the fundamental impulse response at a time in the convolution integral. In practice, the sampling function is limited by the measurement bandwidth and the interval of sampled frequency points. The best window function (i.e., the sampling function in the time domain) depends on the application. Uniform weighting gives the best time resolution. However, by sacrificing time resolution, the side-lobe suppression of the sampling function can be increased. Several types of window functions are reviewed in [13]. For example, a Hamming-weighting function usually gives a good compromise between the time resolution and side-lobe suppression.

In the following, we propose a technique to optimize the window function for a chosen RDL type SAW tag. A similar kind of procedure for increasing antenna pattern measurement accuracy in a compact antenna test range is presented in [14].

C. Optimal Window Function

Assume that we are measuring a reflected signal s occurring at $t = t_s$. Let us further assume that the interference impulse response $v(t)$ is given. Then, the optimized window (or matched filter) maximizing signal-to-interference ratio is given as [15]

$$\mathbf{w} = \frac{1}{\sqrt{\mathbf{s}^H \mathbf{R}_v^{-1} \mathbf{s}}} \cdot \mathbf{R}_v^{-1} \mathbf{s}, \tag{4}$$

where superscript H denotes Hermitian transpose and

$$\mathbf{R}_v = E\{\mathbf{v}\mathbf{v}^*\}, \tag{5}$$

where E is the expectation operator and $*$ denotes complex conjugate transpose.

D. Optimized Interrogation Procedure

When interrogating an RDL-type SAW sensor, only the time delays between reflections are of interest. Therefore, in the proposed procedure, the time delays of reflections are first roughly estimated, and then an optimized window function is formed to obtain the time delay of a given reflection more accurately. Optimal window functions are generated for each reflection individually.

When interrogating the sensor for the first time, its impulse response is obtained from (2) using, for example, a Hamming window function. The time delays of different reflections, τ_n, are first obtained from the impulse response. The interference impulse response is estimated as

$$\begin{aligned} v(t)_n &= s_{11}(t), \quad \begin{cases} t < \tau_n - \tau_{\text{res}}/2 \\ t > \tau_n + \tau_{\text{res}}/2 \end{cases} \\ v(t)_n &= 0, \qquad \tau_n - \tau_{\text{res}}/2 < t < \tau_n + \tau_{\text{res}}/2, \end{aligned} \tag{6}$$

where τ_{res} is the time resolution of the window $\mathbf{w}$, limited by the available BW. The signal vector $\mathbf{s}$ is estimated as

$$\begin{aligned} s_n(t) &= 1, \quad t = \tau_n, \\ s_n(t) &= 0, \quad t \neq \tau_n. \end{aligned} \tag{7}$$

Then, the nth window function is obtained using (4) as

$$\mathbf{w}_n = \frac{\left(e^{j2\pi\tau_n f}\right)}{\sqrt{\mathbf{s}_n^H \mathbf{R}_{v,n}^{-1} \mathbf{s}_n}} \cdot \mathbf{R}_{v,n}^{-1} \mathbf{s}_n, \tag{8}$$

where the term $\left(e^{j2\pi\tau_n f}\right)$ shifts the window in the time domain. The time delay of the nth reflection is obtained from the impulse response calculated using

$$s_{11,n}(t) = F^{-1}\{S_{11}(f) \cdot W_n(f)\}. \tag{9}$$

E. Practical Considerations

When calculating the initial impulse response, it is useful to use the fast Fourier transform (FFT) algorithm. However, when calculating $s_{11,n}$ it may be computationally more efficient to calculate $s_{11,n}$ with a discrete Fourier transform (DFT) only in a limited time region in the close vicinity of τ_n.

In addition, when interrogating the same sensor continuously, it is sufficient to calculate optimized windows only once during the first interrogation, as shown in the experiment described in Section III. This enables more efficient computation and may thus increase the interrogation speed. For example, in the experiment described later, the window function computation done during the first interrogation took approximately 900 ms whereas subsequent interrogations took only 13 ms. The computation was performed with MATLAB software (The MathWorks, Natick, MA) installed in a 1.8 GHz laptop computer.

III. Experimental Results

To experimentally verify the proposed method, an RDL-type lithium niobate ($LiNbO_3$) SAW tag operating at 2.45 GHz was used as a temperature sensor. The tag was attached to an aluminum block along with a reference temperature sensor (Prema 3040 precision thermometer, Prema AB, Kalmar, Sweden). The aluminum block was first cooled down to −20°C and then heated up to 30°C with a resistor. The SAW sensor was interrogated with a network analyzer (Agilent N5230A, Agilent Technologies, Santa Clara, CA) wired to the SAW tag with a coaxial cable and a grounded coplanar waveguide adapter.

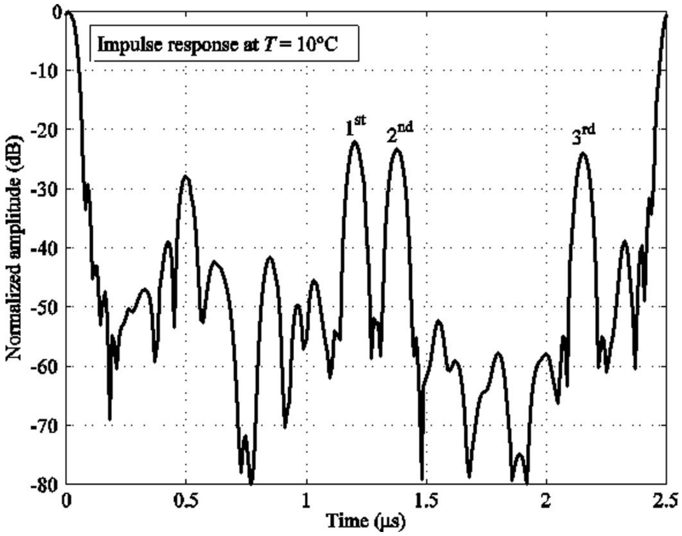

Fig. 2. The measured impulse response of the SAW tag at the temperature of 10°C. The impulse response is calculated from the Hamming-windowed full data set. The temperature response was obtained by calculating the time delay difference between the first and the third reflectors.

The frequency response was measured from 2.25 to 2.65 GHz with a frequency step of 250 kHz (1601 points). A second data set, corresponding to a frequency response from 2.435 to 2.465 GHz with a frequency interval of 400 kHz, was extracted from this complete data set, resulting in a BW of only 30 MHz (1.2%). The full data set was used for reference and the downsampled and truncated test set was used to validate the proposed method. Note that both data sets are from the same frequency response measurement.

The tag had 3 reflectors and the time delay between the first and the third reflector was measured, see Fig. 2. The time resolution of τ_{res} =60 ns (limited by the measurement BW of 30 MHz) was used in (7). For comparison, the temperature response of the tag was also calculated using Hamming window function on the test data set.

The time delay as a function of temperature, calculated from the measured data using the proposed method, is shown in Fig. 3, with comparison to the corresponding temperature response obtained using a Hamming window function in the calculation.

To compare the accuracies provided by the 2 methods, the temperature response of the tag was also calculated using the full data set with a Hamming-window. Due to the wider available BW, the full data set yields considerably higher time resolution in the time delay calculation than the test data set. The deviations of both temperature responses (optimized and Hamming-window) from the reference response calculated using the full data set are shown in Fig. 4.

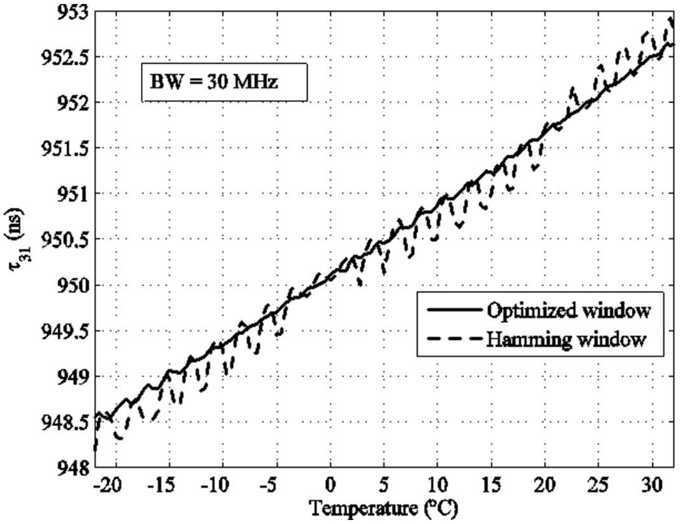

Fig. 3. Temperature response (time delay as a function of temperature) of an RDL-type SAW tag obtained with the proposed interrogation method (solid line) and using a Hamming window (dashed line).

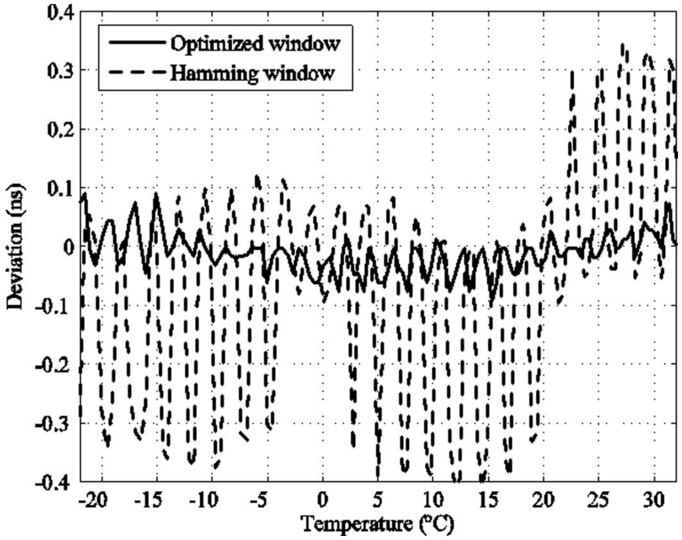

Fig. 4. The deviation of temperature responses obtained from the truncated data set with the proposed interrogation method (solid line) and with a conventional method with Hamming window (dashed line) from the reference response calculated using the full data set.

Let us compare the achieved accuracy of the proposed method to the theoretical limit defined by the Cramer-Rao lower bound (CRLB). Mean deviation of the response obtained using the proposed method from the time delay calculated using the full data set is 0.034 ns (~0.034%), whereas for the response calculated using Hamming windowing, the mean deviation is 0.209 ns (~0.2%). For comparison, the theoretical limit defined by the CRLB for the standard deviation of the estimated time-delay difference is 0.0136 ns. The CRLB for phase-based delay time estimation is calculated from [16]

$$\operatorname{var}\left\{\hat{\tau}_{ij}\right\} = \frac{4}{\left(2\pi f_0\right)^2 NB^2}\left(\frac{1}{\eta_i} + \frac{1}{\eta_j}\right), \tag{10}$$

where var{ } denotes a variance operator, $\hat{\tau}_{ij}$ is the estimated time-delay difference between ith and jth reflectors, f_0 is the center frequency, N is the number of the sampled discrete frequencies, B is the bandwidth, and η_i and η_j are the signal-to-noise ratios of ith and jth reflections, respectively. The estimated signal-to-noise ratios are given as [16]

$$\hat{\eta}_i = \frac{\hat{A}_i^2}{2\hat{\sigma}^2}, \tag{11}$$

where $\hat{A}_i$ is the estimated amplitude of ith reflection. The noise variance is estimated as

$$\hat{\sigma}^2 = \frac{1}{N\left(N_1 - N_0 + 1\right)} \sum_{k=N_0}^{N_1} \left|\mathbf{s}_{11}\left(k\right)\right|^2, \tag{12}$$

where N_0 and N_0 are the limits of the region in the time-domain, where there exist no signals from the reflectors but only white noise. In the above calculations, the noise-only region in the complete data set was selected from 4.5 µs to 7 µs.

IV. Conclusion

In this correspondence, we propose a method for enhancing FMCW interrogation of a wireless RDL-type SAW tag. According to the proposed procedure, when calculating the time response using the Fourier transform, the measured frequency response is windowed such that the signal-to-interference ratio of the impulse response is maximized at given temporal points. Optimized window functions for each temporal point of interest are calculated from the impulse response obtained using a Fourier transform with a non-optimized window function. The optimized functions are used to further refine the calculated time delays of the reflections.

The method is experimentally verified by studying a SAW tag used as a temperature sensor. The time delay could be accurately measured with only a 30 MHz bandwidth at the center frequency of 2.45 GHz. The accuracy of the method is compared both to that obtained using only Hamming-windowing and to the theoretical limit defined by the CRLB. The accuracy of the proposed method is close to the theoretical limit while being considerably better than that of Hamming-windowed Fourier transform.

References

[1] R. M. White and F. W. Voltmer, "Direct piezoelectric coupling to surface elastic waves," *Appl. Phys. Lett.*, vol. 7, pp. 314–316, 1965.

[2] C. S. Hartmann, "A global SAW tag with large data capacity", in *Proc. 2002 IEEE Ultrason. Symp.*, pp. 65–69.

[3] R. Steindl, A. Pohl, and F. Seifert, "Impedance loaded SAW sensors offer a wide range of measurement opportunities," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 12, pp. 2625–2629, Dec. 1999.

[4] A. Pohl, "A review of wireless SAW sensors," *IEEE Trans. Ultrason. Ferroelectr, Freq. Control*, vol. 47, no. 2, pp. 317–332, Mar. 2000.

[5] L. Reindl, G. Scholl, T. Ostertag, H. Scherr, U. Wolff, and F. Schmidt, "Theory and application of passive SAW radio transponders as sensors," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 45, no. 5, pp. 1281–1292, Sep. 1998.

[6] G. Scholl, C. Korden, E. Riha, C. W. Ruppel, U. Wolff, G. Riha, L. Reindl, and R. Weigel, "SAW-based radio sensor systems for short range applications," *IEEE Microwave*, vol. 4, no. 4, pp. 69–76, Dec. 2003.

[7] B. Drafts, "Acoustic wave technology sensors," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 4, pt. 2, pp. 795–802, Apr. 2001.

[8] K. Lee, W. Wang, T. Kim, and S. Yang, "A novel 440 MHz wireless SAW microsensor integrated with pressure-temperature sensors and ID tag," *J. Micromech. Microeng.*, vol. 17, pp. 515–523, 2007.

[9] A. Pohl and L. Reindl, "Measurement of physical parameters of car tires using passive SAW sensors," *Proc. Advanced Microsystems for Automotive Applications Conf.*, 1998, pp. 250–262.

[10] U. Wolff, F. Schmidt, G. Scholl, and V. Magori, "Radio accessible SAW sensors for non-contact measurement of torque and temperature," *Proc. IEEE Ultrason. Symp.*, 1996, pp. 359–362.

[11] V. Kalinin, "Passive wireless strain and temperature sensors based on SAW devices," *Proc. Radio Wireless Conf.*, 2004, pp. 187–190.

[12] R. C. Hansen, "Fundamental limitations in antennas," *Proc. IEEE*, vol. 69, no. 2, pp. 170–182, Feb. 1981.

[13] F. J. Harris, "On the use of windows for harmonic analysis with the discrete Fourier transform," *Proc. IEEE*, vol. 66, no. 1, pp. 51–83, Jan. 1978.

[14] V. Viikari and A. V. Räisänen, "Antenna pattern correction technique based on signal-to-interference ratio optimization," *IEEE Antennas Wireless Propag. Lett.*, vol. 6, pp. 267–270, 2007.

[15] G. Turin, "An introduction to matched filters," *IRE Trans. Inf. Theory*, vol. 6, no. 3, pp. 311–329, Jun. 1960.

[16] S. Schuster, S. Scheiblhofer, L. Reindl, and A. Stelzer, "Performance evaluation of algorithms for SAW-based temperature measurement," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 53, no. 6, pp. 1177–1185, Jun. 2006.