New Applications of Wirelessly Interrogable Passive SAW Sensors

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***Abstract*— Applying passive wirelessly interrogable surface acoustic wave (SAW) sensors, many physical parameters can be measured. Up to now, all SAW sensor applications are performed by taking a snapshot of the sensor's response periodically and evaluating the measurand assumed to be quasi-stationary. Therefore, the upper limit for the rate of sampling of a mechanical affect to the sensor is the interrogation rate. Usually, it is in the range of some tenths of kilohertz or less, measurands with a periodicity of up to a few kilohertz can be sampled satisfactory. Even audible vibrations of machine parts can be monitored. Here, the behavior of the sensors for dynamic measurands is discussed, the mechanisms of interrogation limiting the permissible measurand's bandwidth are described, and error estimations are made. Advanced applications for the measurement of vibration and acceleration, for dynamic pressure measurement in mechanical engineering, e.g., for monitoring the tires of cars, are presented.**

***Index Terms*—Dynamic measurements, SAW delay lines, SAW sensors.**

I. Introduction

For many applications, where a cable connection between the locations of a sensor and the measurement system cannot be established, wireless sensing is necessary. Therefore, active transponder systems have been developed containing semiconductors, capacitors, and a power supply like batteries or inductive remote-powering circuits. The employment of these circuits usually is subject to narrow limitations due to lifetime and environmental conditions like heat, radiation, electromagnetic interferences, etc. A few years ago, passive wirelessly interrogable surface acoustic-wave devices were introduced for remote sensing [1], [2]. On the plain polished surface of a piezoelectric substrate, a number of metallic structures interdigital transducers (IDT's) are arranged. An RF signal, transmitted by an interrogator unit, is received by the sensor's antenna and is fed into the only connected IDT of the device. In Fig. 1, the principle of a wirelessly interrogable passive SAW sensor and the signals during an interrogation period are sketched.

The electric RF voltage on the IDT connected to the antenna excites a surface acoustic wave propagating along the substrate's surface. In the propagation path, electroacoustic reflectors are located and the SAW is partially reflected. The waves arrive at the exciting IDT after a time interval corresponding to the ratio between the doubled geometric length of the propagation path and the velocity of the SAW. Here, these SAW components are converted back into RF signals and are retransmitted to the interrogator. The interrogator receives this signal train and converts it into an intermediate frequency band or to baseband range, respectively (Fig. 2).

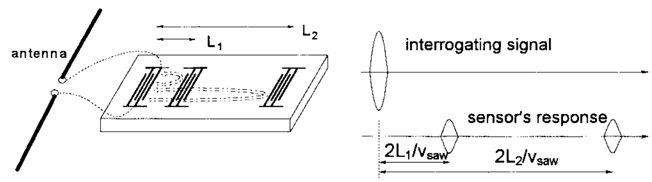

Fig. 1. Wirelessly interrogable passive SAW sensor and signals during interrogation cycle.

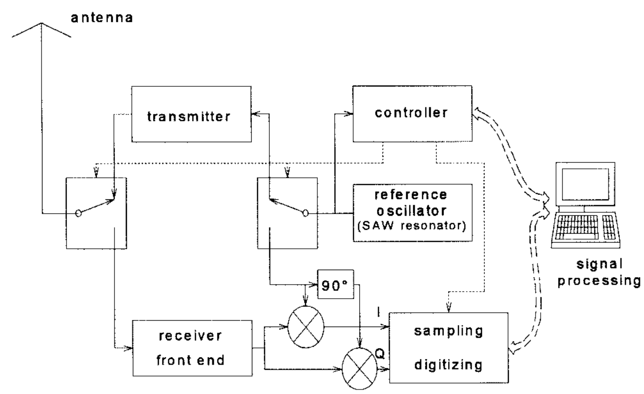

Fig. 2. System for interrogation of passive SAW sensors.

Usually the signal is sampled and the magnitude and phase of the sensor's response impulses versus time are evaluated.

If the sensor is affected by a measurand, the substrate's length and its elasticity constants are changed, changing the SAW's velocity and the attenuation. Thus, if the sensor is heated, stretched, or compressed, or if it is loaded to be bent, the sensor's response to the interrogation signal is scaled in time by a factor $s = 1 + \varepsilon$, all delays τ_i become $\tau_i' = s \cdot \tau_i$. Shown in Fig. 3, the information about absolute or differential delay is obtained by sampling of the received sensor's response and further signal processing. The measurand scaling this response can be calculated from the measured delays τ_i.

If only the delay between two response bursts is measured, the resolution will be poor. A 10-MHz system's bandwidth yields a duration of about 100 ns of the interrogation burst and of the impulses retransmitted from the sensor. Looking at the envelope of the response in time domain only, shifts of about 10 ns can be detected. For example, for temperature

Manuscript received March 13, 1998; revised August 27, 1998.

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Publisher Item Identifier S 0018-9480(98)09219-9.

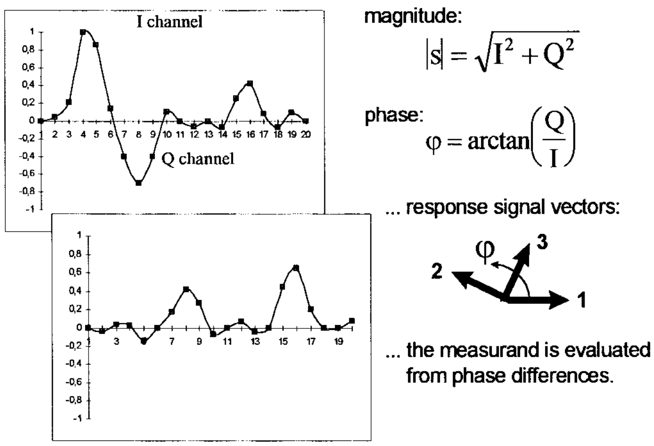

Fig. 3. Signal processing for interrogation.

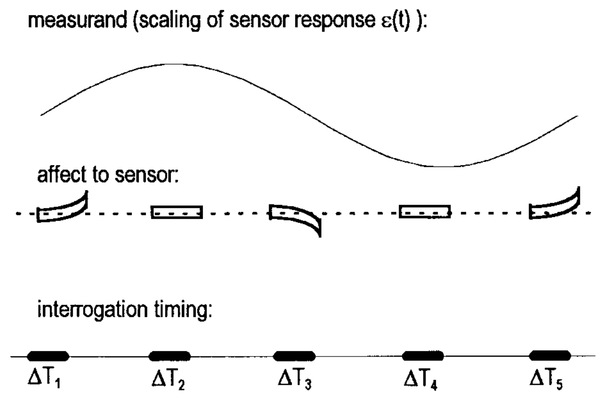

Fig. 4. Interrogation of SAW delay-line sensors affected by a dynamic measurand.

measurements a Lithium Niobate ($LiNbO_3$) delay line with a delay sensitivity of approximately 80 ppm can be applied advantageously. For a sensor with an absolute delay of 6 μs (20-mm propagation distance), a delay of 10 ns represents 1660 ppm of the full span. Therefore, the resolution is approximately 1660/80 $\approx$ 20 K, which is rather poor for precision measurements.

If the coherent receiver concept shown in Fig. 2 is applied, the reference oscillator in the system the transmitted burst was derived from, can be used as a ruler in time, and the relative phase of the response impulses can be measured.

The phase measurement's resolution depends on the noise of the received signal and the digitization of the baseband quadrature signals. If it is processed using 8 bits and the dynamic range is modulated fully, the phase can be measured with a resolution of better than 1°; 1° in time domain represents a delay of 1/360 of one RF period. For a 433-MHz interrogator, 1° corresponds to a delay of 2.3 ns/360 = 6.4 ps. Thus, for the assumed parameters, the resolution can be enhanced from 10 ns to 6.4 ps or from 20 to 0.0128 K in optimum.

In practical use, the resolution is limited to approximately 0.1 K due to noise and insufficient modulation and level control, respectively, at the sample unit.

In comparison with other wireless sensor systems, the main advantage is that SAW sensors are total passive. Since they contain no semiconductors nor capacitors or other electronic components, they are not limited in such a narrow manner by operating temperature, radiation, etc. The upper temperature limit is given by the melting temperature of the used metals and the piezoelectric curie temperature of the substrate (here, the piezoelectric effect vanishes), respectively. SAW sensors consist of a substrate (e.g., Quartz, Lithium Niobate, etc.) and planar metallic structures on its surface. The capability to withstand mechanical load is that of the crystal itself.

The problems in practical use are that the sensor have to be encapsulated hermetically since every dust on the surface will cause absorption of the SAW and cause a fail of the sensor. Further, in comparison with radio sensors powered by a battery, similar to a RADAR scenario with passive reflectors, the attenuation of the electromagnetic wave between the interrogator and the sensor depends on the fourth power of distance. Thus, the feasible distance for interrogation with permissible radio transmission is limited to approximately 20 m. Usually, as RADAR technique, coherent integration measures are applied, the results are averaged in time for a number of interrogation cycles. This yields more signal energy E_s in the total sensor's response used for further signal processing and reduces the errors due to noise calculating the measurand. Further it helps to match to the governmental regulations for wireless telemetry systems. The energy E_S is divided to k interrogation signals, the power required for each of these is by a factor k smaller.

In a number of publications applications for identification purposes, temperature, bending, and torque measurement have been published [3]–[5]. The measurand is converted to a thermal, mechanical, or electrical effect to the sensor and its SAW propagation path, respectively.

All applications published are characterized by a quasi-stationary behavior of the measurand.

In this paper, we present the measurement of dynamic processes. In Section II, the limits and possible errors for these purposes are discussed. Then two experimental measurement results are shown. A brief conclusion summarizes the contents of the paper.

II. Dynamic Measurements

In this paper, we will relate to the SAW delay-line sensors shown above. Therefore, limits have to be considered when operating the devices to measure with high resolution in time. The effect of the measurand, the scaling of the sensor's response due to the mechanical or the thermal extension, and the change of crystal's constant is denoted by $\varepsilon(t)$. Here, f_ε denotes the frequency of the periodic, e.g., mechanical, effect to the sensor. If the effect to the sensor is not periodical, f_ε can be assumed to be the highest Fourier spectral component of the exciting measurand. The time ΔT denotes the measured delay between the interrogation burst and the response of a simple SAW delay-line sensor with one reflector or between two reflectors on the surface of a sensor, respectively.

For many applications, the measurand is said to be stationary during the reflective propagation of the acoustic wave in the SAW device. The actually delay ΔT is calculated to be a sample of the measurand (Fig. 4). In Fig. 4 the effect to the

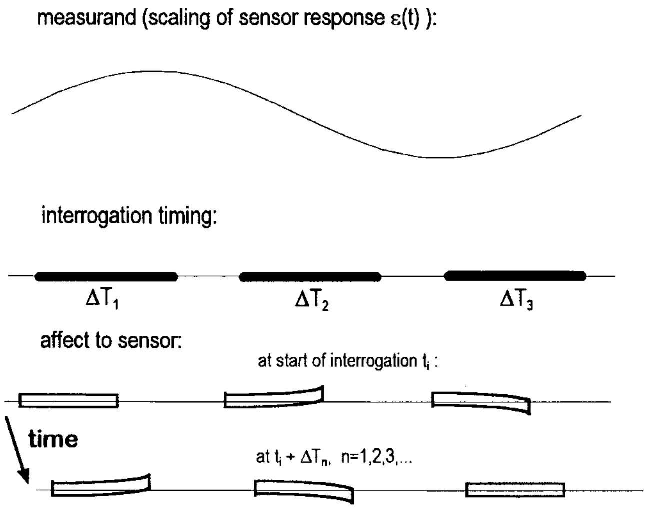

Fig. 5. Interrogation of a delay-line sensor for fast-changing measurands.

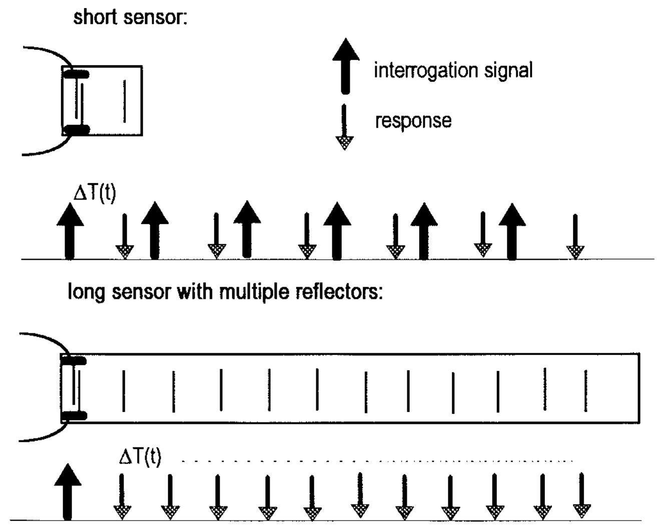

Fig. 6. SAW delay-line sensors for dynamic measurands.

sensor is drawn as bending of the substrate, representing a mechanical measurand. In general, the behavior is identical for all kinds of measurands.

As shown in [4], this approximation of sampling fails if this stationary condition is broken. Then, the scaling changes during one interrogation cycle for a term not negligible anymore.

If we assume that the measurand changes periodically with a sine function, the actual scaling $\varepsilon(t)$ is

$$\varepsilon(t) = \varepsilon_{\max} \cdot \sin(2\pi \cdot f_\varepsilon + \varphi_{\text{sample}}) \tag{1a}$$

with the phase angle φ_{sample} of the measurand's periodicity where the interrogation is started.

Usually, the scaling will be an unknown function of time and sampling time t_s

$$\varepsilon(t) = f(t + t_s). \tag{1b}$$

In Fig. 5, the timing and effect to the sensor element is sketched for a measurand, where the assumption of being stationary, mentioned above, is violated.

The effective scaling ε_{eff}, the scaling measured or displayed, respectively, by the interrogation system is

$$\varepsilon_{\text{eff}} = \frac{1}{\Delta T} \cdot \int_{\Delta T} \varepsilon(t)\, dt. \tag{2}$$

If for the periodic $\varepsilon(t)$ the sensor's delay ΔT is the same as the period length of the exciting measurand, the effect will be masked. From the equations above, it can be seen that, with sensors with a number of reflectors for special applications, the information about $\varepsilon(t)$ can be gained by parameter estimation even for high measurand's frequencies f_ε and delay intervals ΔT if the course of the measurand is known, and e.g., only magnitude and phase are unknown.

Otherwise, in general, the course of sensor's scaling due to the measurand has to be sampled according to the Shannon's theorem. At least two sample points must be recorded every period of the highest spectral component of the measurand and the scaling $\varepsilon(t)$, respectively.

This sampling can be achieved by sensors with a short substrate length and, therefore, with small ΔT by using a high interrogation rate. It also can be achieved by periodical arrangement of n reflectors with a spacing ΔT. The sensor's response time is increased to $n \cdot \Delta T$, the interrogation rate is decreased approximately by a factor n. In Fig. 6, both sensor types are drawn.

For both types, distinguishing the impulses of the sensor's response interrogation pulses shorter than ΔT are necessary, requiring a bandwidth larger than $1/\Delta T$. If every delay is evaluated, the sample rate applied to the measurand is $1/\Delta T$, the interrogation bandwidth. Within these intervals ΔT, the sensor's scaling is integrated, according to (2). For sampling, this integration time intervals must be short compared to the period $1/f_\varepsilon$ of the frequency of the signal to measure.

The spacing ΔT is chosen to be $1/N$ of the period, $1/f_\varepsilon$, of the measurand $\varepsilon(t)$ or its highest Fourier component, respectively. More than two samples are recorded during a period of $\varepsilon(t)$. Therefore, a maximum bandwidth of the dynamic measurand up to $1/N$ of the interrogation bandwidth can be achieved.

Depending on the admissible error, dynamic processes up to a frequency of some megahertz can be measured with passive wirelessly interrogable SAW sensors.

The error due to this integral sampling can be estimated from the factor N, assuming a periodically changing measurand with a sine course. Therefore, with equal spaced delay intervals ΔT, the maximum error will appear for the maximum change of the measurand within ΔT. For a sine course of $\varepsilon(t)$, the derivation of the sine is a cosine, the maximum can be observed at zero crossing; the gradient in time is one. For a large N, the sine function can be linearized there. Thus, the maximal error occurs if the integral of $\varepsilon(t)$ in the interval ΔT yields zero since it passes zero. Then, the error is $\pm\sin(2\pi/N)$.

For $N = 10$, if a measurand with a bandwidth of 1 MHz is measured using a system with an interrogation bandwidth of 10 MHz, utilizing 100-ns bursts and reflector spacing, respectively, the error of the samples already can grow up to 30%.

For dynamic measurements, where the measurand changes rapidly, some further practical aspects have to be considered.

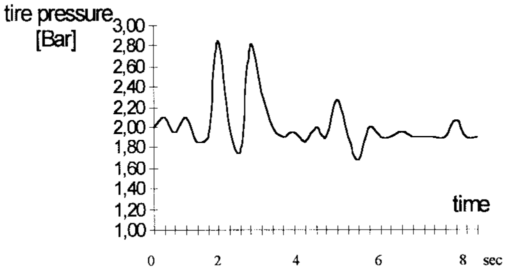

Fig. 7. Pressure in car tires overriding a two-track railway crossing.

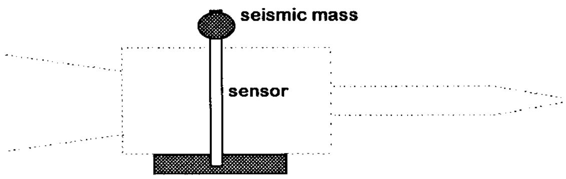

Fig. 8. Measurement of acceleration and deceleration of a Dart arrow.

In general, for dynamic measurements, the system has to be able to perform fast signal processing. For on-line monitoring, high amounts of calculation power has to be spent. If the process should be monitored off-line only, the data can be stored in an extensive memory. The access to the memory cells have to be fast. Solutions with banks of random access memory (RAM) with access time intervals of less than 10 ns switched by turns have been built for measurements.

To avoid such extensive signal-processing effort, strategies for data reduction must be implemented. Therefore, with a kind of asynchronous sampling, only the information necessary for calculation of the measurand can be recorded for calculation. All sampling information of noise and other RF signals in between are thrown away to relieve the signal-processing circuits.

III. Experimental Measurements

First, the measurement of tire pressure in car tires in motion is discussed. Here, a dynamic pressure measurement is possible, implementing passive SAW sensors.

In Fig. 7, the air pressure in a front wheel of a car is drawn while the vehicle passes a railway crossing with two tracks and an adjacent water channel.

Due to the shocks while the car "falls" into the grooves between the rails, a rapid increase of pressure can be observed. Applying SAW sensors, a wireless dynamic measurement of tire pressure can be achieved.

As another example of dynamic measurement, the implementation for vibration and acceleration measurements is proposed.

To proof the capability of the principle, we performed measurements with a SAW sensor fixed to a Dart arrow (Fig. 8).

The passive sensor was fixed right angled to the handle of the arrow. For acceleration and deceleration, the sensor is bent. For small displacements, the scaling of the response is proportional to the force F at the seismic mass m. The acceleration $a = F \cdot m$ can be calculated.

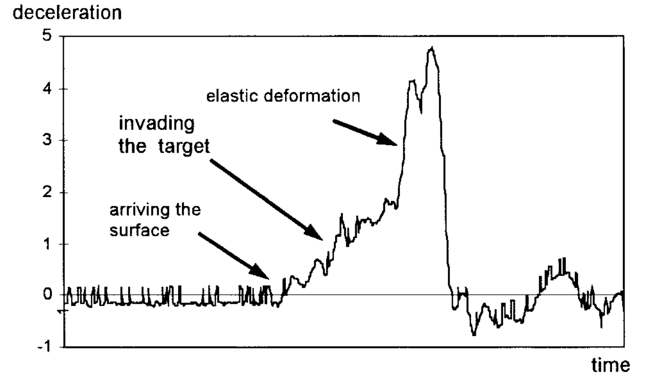

Fig. 9. Deceleration of the arrow invading the target made of foamed polyethylene.

Measurements of the deceleration in the phase of invading into the target are shown in Fig. 9.

Arriving at the target's surface, the arrow is decelerated almost linearly due to the almost cylindrical head. Then, the handle causes elastic deformations of the target's material connected with a peak of the deceleration, followed by a decaying oscillation.

IV. Conclusion

It is well known that passive SAW sensors are capable of measuring a lot of physical parameters. Due to their passive behavior and the materials used, they are able to operate in environments characterized by hostile conditions. SAW sensors have fast electrical response and they are useful even for high measurement rates. Up to now, SAW sensors are assumed to take snapshots and the measurands are stationary for the time interval of the sensor's response length. If the change of the measurands is faster, errors occur.

In this paper, it was shown that the upper limit of the capability of SAW sensors to measure dynamic processes is given by $1/N$ of the interrogation bandwidth. Therefore, with the Shannon's sample theorem and permissible error, the maximum resolvable frequency of the measurand is up to some megahertz for today's SAW sensor systems. A lot of advanced applications become feasible where fast dynamic processes have to be observed using reliable passive sensors.

Acknowledgment

The authors thank L. Reindl and Dr. C. Ruppel, Siemens Corporate Research, Munich, Germany, for supporting this work with excellent SAW devices and helpful discussions.

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