Autonomous Battery-Less Wireless Strain Gage for Structural Health Monitoring

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ABSTRACT:

Strain and temperature are important measurements for structural health and integrity. High magnitude and repetitive variations of these two parameters may lead to fatigue or yielding in the material or even failure of the structure. Strains can be used to estimate the loads, moments, and stresses on structures, or to measure torque, pressure, and acceleration.

Since the surface acoustic wave (SAW) devices are sensitive to various physical parameters, including strain and temperature, they can be used as sensors of these parameters. They are passive (no power supplies (e.g. batteries) are required), they are very small (1 to 3 mm²), they can embed an identification code so that multiple sensors can be used simultaneously within the reading range of the interrogator and they can be used in extreme environments (e.g. temperatures from cryogenic values up to more than 1,000°C).

SAW devices are also well suited for wireless communication. A wireless sensor system consists of SAW sensors/transponders and a radar like interrogator reader. In order for SAW sensors to become ubiquitous, several problems have to be solved. The major challenge is to separate the influence of different physical parameters on the sensor response. The second challenge is to make the sensors operate over a wide temperature range. Both problems have been solved by Albido.

DESCRIPTION OF THE TECHNOLOGY

SAW sensors are monolithic structures fabricated with current IC photolithography techniques, which makes them small and rugged. Compared to current IC technology, SAW sensors are simple to fabricate. They only use one or two photolithography steps as compared to more than 20 for a standard IC.

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The following gives an overview of our SAW sensors, the principle of operation and some recent results. There are essentially two types of SAW sensors (1) a structure with 2 separate interdigitated structures (IDT) for input and output as shown in Figure 1 and (2) a device with only one set of interdigitated structures that serves both as input and output and a set of reflectors. This device, as shown in Figure 2, operates essentially in a resonant mode.

As shown schematically in Figure 3, an RF pulse is transmitted by the interrogator and is received and reflected back by the SAW sensor/transponder. The frequency, the phase, and the amplitude of the reflected RF signal are a function of the piezoelectric parameters of the substrate, the geometrical characteristics of the interdigitated electrodes and the associated reflectors (as shown in Figures 1 and 2), but also a function of the environmental parameters, such as temperature, strain, humidity, etc. The SAW sensors can operate in a wide frequency range, from below 100 MHz to above 3 GHz. One of the challenges of the proposed technology is how to perform anti-collision schemes in order to operate multiple SAW sensors (up to several hundred) in the same area. One way to implement anti-collision is with different multiplexing methods. Depending on the application, one or a combination of the following methods: TDMA (Time Division Multiplexing Access), FDMA (Frequency DMA), CDMA (Code DMA), OFC (Orthogonal Frequency Coding), or SDMA (Spatial DMA) can be used.

A reading range of up to 20 meters or even more can be achieved. This depends on the operating frequency, the sensor geometry and the nature and shape of the objects in close proximity, and how many sensors are within the reading range of the reader system.

The distance between two fingers of the same polarity is termed the electrical period \( q \) of the IDT. The maximum electroacoustic interaction is obtained at the frequency \( f_0 \), the mid-frequency of the transducer. At this frequency the wavelength \( \lambda_0 \) of the surface acoustic wave precisely corresponds with the electrical period \( q \) of
the IDT, so that all wave trains are superimposed in-phase and transmission is maximized

\[ q = \lambda_0 = v f_0 \]  
(1)

The relationship between the electrical and mechanical power density of a surface wave is described by the material-dependent piezoelectric coupling coefficient \( k^2 \). Around \( k^2 \) overlaps of the transducer are required to convert the entire electrical power applied to the IDT into the acoustic power of a surface wave. The velocity \( v \) of a surface wave on the substrate, and thus the propagation time \( \tau \) and the mid-frequency \( f_0 \) of a surface wave component, can be influenced by various physical and/or chemical variables. In addition to temperature (1) mechanical forces such as static elongation, compression, shear, bending and acceleration have a particular influence on the surface wave velocity (2). This facilitates the remote interrogation of mechanical forces by surface wave sensors. To first order, the influence of the quantity \( y \) (which can be temperature, strain et al.) on the mid-frequency \( f_0 \) and propagation time \( \tau \) can be calculated as follows:

\[ v(y) = v(y_0) \cdot [1 - S^y_y \cdot (y - y_0)] \]  
(2)

\[ f_0(y) = f_0(y_0) \cdot [1 - S^f_y \cdot (y - y_0)] \]  
(3)

\[ \tau(y) = \tau(y_0) \cdot [1 + S^\tau_y \cdot (y - y_0)] \]  
(4)
If only the differential propagation times or the differential phase between the individual reflected pulses are evaluated, the sensor signal is independent of the distance between the reader and the transponder. The differential propagation time $\tau_{2-1}$, and the differential phase $\varphi_{2-1}$ between the two received pulses is obtained from the distance $L_{2-1}$ between the two reflectors, the velocity $v$ of the surface wave, and the frequency $f$ of the interrogation pulse.

$$\tau_{2-1} = \frac{2 \cdot L_{2-1}}{v}, \quad \varphi_{2-1} = 2 \pi f \cdot \tau_{2-1} = \frac{4 \pi f \cdot L_{2-1}}{v} \tag{5}$$

The measurable change $\Delta \tau_{2-1}$ or $\Delta \varphi_{2-1}$ when a physical quantity $y$ is changed by the amount $\Delta y$ is thus:

$$\Delta \tau_{2-1} = \tau_{2-1} \cdot S_y \cdot \Delta y; \quad \Delta \varphi_{2-1} = 2 \pi f \cdot \tau_{2-1} \cdot S_y \cdot \Delta y \tag{6}$$

The influence of the physical quantity $y$ on the surface wave transponder can thus be determined just by the evaluation of the phase difference between the different pulses of the response signal.

Similar to RFIDs, SAW sensors are powered by the electromagnetic field emanating from the reader/interrogator system. The optimal frequency is in the MHz to GHz range. There is a difference of about 5 orders of magnitude in the communication frequency and the surface acoustic wave frequency. This means, that we don’t have to worry about signal reflections that plague many of the competing systems. A system based on SAW sensors should be immune to signal reflections which makes it ideal for application in a metallic environment (e.g. inside a jet engine).

*Figure 3 Schematic of a SAW-based radio-link measurement system*
As mentioned before, Albido has solved the problem that SAW sensors cannot easily distinguish between various physical parameters. For example, SAW sensors are sensitive to temperature and strain. If the temperature is not constant it is not clear whether the sensor response is due to a temperature change or strain. Albido has developed a methodology to distinguish between the effects of various physical parameters and has applied for a patent on its solution.

**Figure 4** Frequency vs. strain response of a representative sensor

**Figure 5** Frequency vs. strain response of a representative sensor with temperature as a parameter
EXPERIMENTAL RESULTS

Figure 4 shows the frequency versus strain variation for quartz based SAW sensor with resonant frequency equal to 432.27 MHz. The reading range was about 3 m with 10 mW RF power from the reader and an unoptimized antenna. Figure 5 shows the frequency versus strain response with temperature as a parameter. It is clear from Figure 5 that it is critical that a methodology is found to separate the effects of strain and temperature from the sensor response.

CONCLUSIONS

Recently, surface acoustic wave (SAW) devices have been used as sensors. Depending on the substrate material chosen, they can cover a wide temperature range. They are simple to fabricate: they require only 1 or 2 photolithography steps (as compared to more than 20 for standard IC processing), they are small (~ 1 x 3 mm) and, therefore, inexpensive. They are quite sensitive to many physical parameters such as temperature, strain/stress, humidity, pressure, etc. but also to chemical contaminants. They are ideally suited for wireless communication since they require an electromagnetic field for power that can also be used for communication. We believe that these sensors are ideally suited for structural health monitoring (SHM), especially in applications where small, localized defects have to be detected. It is important that the sensors can distinguish between different physical parameters (e.g. temperature and strain). Albido has solved this problem and has applied for a patent on the solution. Also, Albido’s sensors cover a wide temperature range, from cryogenic temperatures (e.g. -60 °C) to temperatures in excess of 1,000 °C.
REFERENCES


