Wireless read-out of a resonant temperature sensor over an acoustic channel

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Abstract - For saving weight and reducing resources, fiber-reinforced polymers are commonly used for pressure tanks. To monitor process parameters inside the tank, wireless sensor systems are desired to avoid a reduction in structural integrity or hermeticity due to additional holes or wire feedthroughs through the shell of the tank. However, since carbon fiber reinforced polymers (CFRP) are electrically conductive, wireless sensor systems based on electromagnetic waves cannot be used in these applications.

This contribution, therefore, presents a measurement technique to wirelessly read out a resonant sensor exploiting an acoustic communication channel through an electrically conductive transmission medium. This passive wireless sensor technology consists of a read-out unit and an analog sensor node located inside the tank. The sensor node comprises an electromechanical transducer and a resonant temperature sensor with a high mechanical quality factor. The sensor node is read out using a pulse-echo method in which the resonator is excited by a sinusoidal pulse from the read-out unit. The decaying echo of the resonator is backscattered and the temperature-dependent resonance frequency can, thus, be extracted with a time domain separation in the read-out unit.

We will show a wireless passive resonant temperature measurement with coaxially coupled piezoceramic ultrasonic transducers through a 10 mm thick CFRP plate with a software defined read-out unit and a temperature sensitive quartz crystal resonator. A typical temperature range for CFRP from -40 to 110 °C is demonstrated in the measurements.

Keywords – acoustic passive wireless sensor technology, high-Q resonator, resonant sensor, acoustic feed-through, passive temperature sensor.

I. INTRODUCTION

Acoustic waves are preferred over electromagnetic waves for the transfer of data and energy through a liquid or solid transmission medium with electrical conductivity or high permittivity due to their better propagation properties. A variety of sensor systems utilize an acoustic channel to communicate through solids such as metals or modern carbon fiber reinforced polymers, liquids as well as human or animal tissue. A sensor node is thereby often operated inside an enclosure. It is supplied with an acoustic energy transfer (AET) and collects data and transmits it back over the acoustic channel. In the sensor node, the acoustic energy is in most cases converted with an electromechanical transducer and rectified to be able to supply a digital circuitry [1]. If the energy is not sufficient for the continuous operation of the sensor node, it will be temporarily stored in an electrochemical cell. As the barrier can represent the hull of a tank, there could be potential harsh environmental conditions enclosed in it, where the operation of a highly integrated electrical circuitry and the functionality of an electrochemical cell cannot be guaranteed to be maintenance-free and long-lasting.

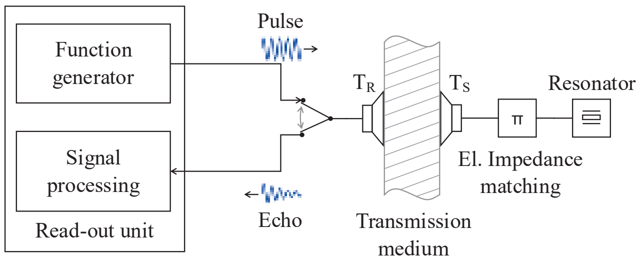

Fig. 1: Schematic measurement concept of an acoustic passive wireless sensor system with a pulse-echo method.

In contrast, passive wireless sensor technology is based on purely analog sensors that can be read out wirelessly without requiring a battery. Since theoretically all the received energy from a passive sensor node can be backscattered to a read-out unit, the measurement systems are potentially highly energy-efficient. As there are no minimal thresholds for operation as with digital circuitry, they can be operated down to the noise floor [2]. Due to these properties and the low complexity of the sensor node, the resulting measurement systems are considered to be maintenance-free, lightweight, smallscale and reliable [3].

A passive wireless sensor technology with an acoustic communication channel over air has been shown in [4]. In this contribution, an acoustic passive wireless sensor system will be presented for the first time. The measurement system operates through an electrically conductive transmission medium.

II. MEASUREMENT CONCEPT

The measurement concept of the acoustic passive wireless sensor system shown in Fig. 1 consists of a read-out

ISBN 978-3-8007-5835-7

unit and a passive sensor node. They are coupled over an acoustic channel formed by the electromechanical transducers of the read-out unit T_R and the sensor node T_S, which are coaxially attached to opposite sides of a transmission medium.

The key component of the passive sensor node is a resonator with a high quality factor, whose resonance frequency f_0 is a function of the quantity to be measured, such as temperature, pressure or other physical quantities. As one of the most relevant parameters for many technical processes, the temperature ϑ is further investigated in this contribution.

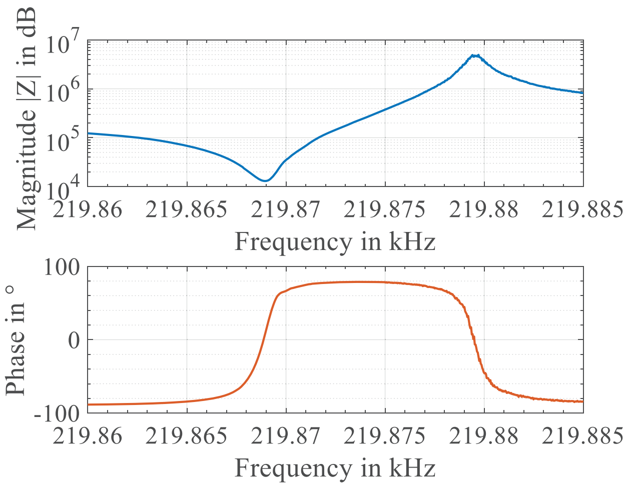

Fig. 2: Impedance measurement of the resonator at room temperature with a high precision impedance analyzer HP 4294A.

The passive sensor node is read out with a pulse-echo method. The read-out unit thereby sends an excitation pulse, which is transmitted to the sensor node with the electromechanical transducer T_R. The incident acoustic signal at the sensor node is converted with the transducer T_S and electrically excites a resonant sensor to oscillate. If the temperature dependent resonance frequency $f_0\,(\vartheta)$ is within the bandwidth of the excitation pulse, the resonator stores this energy in a weakly damped oscillation. After the end of the excitation pulse, the resonator is decaying in an exponentially decaying function with an amplitude $A(t)$ of

$$A(t) = A_0 \cdot \mathrm{e}^{-t/\tau} \tag{1}$$

where A_0 denotes the maximum amplitude of the echo after turning of the excitation pulse at time t_0. The time for excitation and decaying depends on the quality factor Q of the resonator with its decay constant τ:

$$\tau = \frac{Q}{\pi \cdot f_0}, \tag{2}$$

whereby the quality factor Q is defined by

$$Q = \frac{f_0}{B}. \tag{3}$$

This decaying signal is scattered back to the read-out unit over the acoustic channel. From this echo, we can extract the resonance frequency $f_0\,(\vartheta)$. To differentiate the excitation pulse and its reflections inside the transmission medium from the resonance frequency $f_0\,(\vartheta)$, the decay time of the resonant sensor has to be longer than the reflections of the pulse. For this, a resonant sensor with a high quality factor Q is required. In [5], commonly used excitation and decaying times are given as 3 to 5 τ for pulse-echo systems with passive read out surface acoustic wave transponders.

III. DESIGN OF THE MEASUREMENT CONCEPT

To demonstrate the functionality of the acoustic passive wireless sensor technology, we implemented a temperature measurement through a 10 mm CFRP plate. Hereby, the transmission characteristics of the electromechanical transducers have to be matched to the resonator's frequencies in the desired temperature range.

A temperature sensitive quartz tuning fork resonator from Statek Corporation with a resonant frequency of 219.87 kHz at room temperature of its fundamental torsional vibration mode serves as resonant sensor. It has a nearly linear temperature sensitivity of $\alpha = 46.4$ ppm [6]. The temperature sensitivity can be described with a second order polynomial

$$f_0(T) = (\beta \cdot \Delta T^2 + \alpha \cdot \Delta T + 1) \cdot f_0(T_0) \tag{4}$$

with temperature T and $\Delta T = T_0 - T$ [6, 7].

From the impedance measurement in Fig. 2, the bandwidth $B = 1.13$ Hz around the resonance frequency can be determined at a phase of -45 ° and +45 ° around the resonance f_0. With Eq. (2) and (3), an unloaded quality factor of $Q = 195000$ with a decay time τ of 282 ms can be derived.

To clearly distinguish, the terminology resonator is used only for the sensing element. Piezoelectric discs are exploited for the electromechanical transducers T_R and T_S.

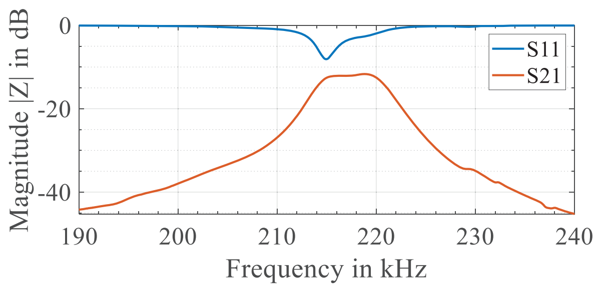

Fig. 3: S-Parameter measurement of the piezoelectric disc transducers.

As electromechanical transducers, a pair of piezoelectric discs from StemInc with a diameter of $\emptyset = 10$ mm and a thickness of $t = 2$ mm with a wraparound electrode is selected. This piezoelectric disc has its fundamental radial mode at 215 kHz ± 5 kHz. The radial mode allows significantly smaller geometric dimensions at this low frequencies while maintaining good coupling and focusing of the central main lobe with a longitudinal wave propagation in axial direction in a modified Bessel function [8, 9].

For the electrical characterization of the acoustic transmission properties, the scatter parameters (S-parameters) of the piezoelectric discs are measured as an electrical two-port with a vector network analyzer across a 10 mm CFRP plate as the transmission medium. The discs are mounted with a silicon rubber adhesive. Fig. 3 shows the electromechanical transmission of the fundamental radial mode with a maximum transmission of $S_{21} = -11.7$ dB at 218.85 kHz. Since it is a reciprocal network, only S_{11} and S_{21} are shown. With the reference impedance $Z_0 = 50\ \Omega$, the electrical impedance of a piezoelectric disc can be derived from the input reflection S_{11} with the well-known parameter conversions.

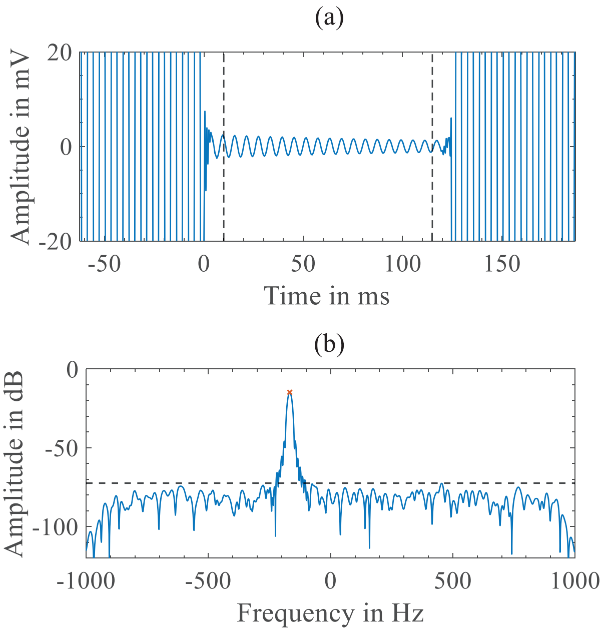

Fig. 4: (a) Measured time domain signal with pulse and echo of the resonant sensor at 0 °C after downconversion and (b) the further evaluated echo signal in the frequency domain.

Due to the significant difference in the electrical impedance between the piezoelectric transducer T_S and the resonator, we tuned the electrical load seen by the resonator with an impedance matching network. The resonator impedance at room temperature at resonance f_0 equals $Z = 13$ kΩ while the electrical impedance of the piezoelectric transducer is $|Z_{avg}| = 273\ \Omega$. Note that the transducer's impedance represents the averaged value over the frequency range of 219.8 ± 1 kHz. A surface-mounted transformer is used for this purpose, which has low losses at low frequencies.

IV. RESULTS

Figure 4 shows an exemplary time domain signal after downconversion with a local oscillator (LO) at 219.8 kHz and a bandwidth of 2 kHz for the measurement at 0 °C. The signal has been downconverted in the read-out unit to reduce computational effort for subsequent signal processing. An excitation pulse with 125 ms duration is applied up to time $t = 0$ ms, with the subsequent decaying echo between 0 to 125 ms. This is followed by the next excitation pulse. The synchronization of the excitation pulse and the echo signal is achieved by an envelope detector. The duration of pulse and echo were empirically determined to be 125 ms to have a sufficient measurement rate. Due to the measurement rate of 4 Hz, highly dynamic temperature changes can be monitored and kept in close frequency tracking.

For further determination of the resonance frequency, the gray dashed lines in the time domain mark the area, which is transferred to the frequency domain. The excitation signal is separated in the time domain from the analysed echo with a duration of 10 ms. The resonance frequency is narrowbanded and has a high signal to noise ratio of 60 dB. This leads to a precise determination of the corresponding temperature.

To determine a sufficient time domain separation, a mechanical quality factor of 1800 is assumed as the longest decaying interfering signal τ_n. With this assumption, a decay constant τ_n of 2.6 ms for the interfering noise signal can be derived which would be reduced to less than 2 % of its initial amplitude after 10 ms according to Eq. (1). To verify that all reflections in the transmission medium have decayed within the specified time domain separation, Fig. 5 shows a pulse-echo measurement of the entire setup without a connected resonator.

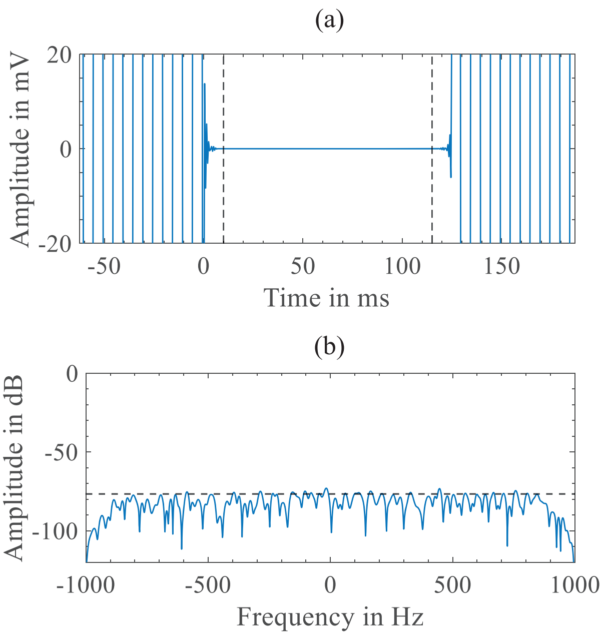

Fig. 5: (a) Measured time domain signal with pulse and echo without an attached resonator and (b) the further evaluated echo signal in the frequency domain.

A temperature profile is conducted in a climate chamber over the applicable temperature range of a CFRP with typical material parameters. The extracted resonance frequency $f_0(\vartheta)$ of each pulse-echo measurement is shown over time in Fig. 6. The signal strength was higher than 50 dB throughout the entire duration of the measurement.

A linear temperature sensitivity of $9.98\ \mathrm{Hz/°C}$ or $45.4\ \mathrm{ppm/°C}$ is observed over the entire temperature range.

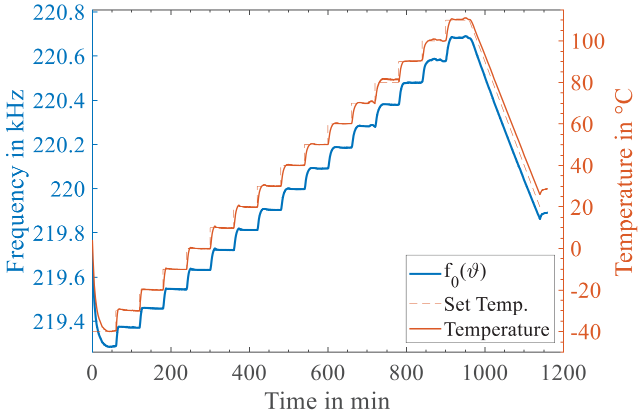

Fig. 6: Wirelessly extracted resonance frequency $f_0(\vartheta)$ through a 10 mm CFRP plate from -40 to 110 °C over time.

V. CONCLUSIONS

We have presented an acoustic passive wireless sensor system to read out a resonant temperature sensor across an electrically conductive barrier. The electromechanical transducers and the high Q temperature sensitive resonator of the passive sensor node have been electrically characterized. A temperature measurement through an electrically conductive carbon fiber reinforced polymer has been demonstrated over a temperature range of -40 to 110 °C with a signal-to-noise ratio of at least 50 dB.

This promising instrumentation technique of the passive wireless sensor technology in combination with an acoustic communication channel could potentially extend the scope of applications in which a wireless sensor is indispensable.

VI. REFERENCES

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