DEVELOPMENT OF SURFACE ACOUSTIC WAVE PRESSURE SENSORS FOR MONITORING CONCRETE STRUCTURES

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ABSTRACT

For many years, surface acoustic waves (SAW) have been used in manufacturing electronic components for industrial and sensing applications. Due to the absence of an embedded electronic system and the possibility of wireless communication, this technology can offer a great solution for sensing in harsh environments such as high pressure, temperature and humidity. In the case of refractory concretes, the optimization of the drying cycles has indeed a significant economic impact (reduction of the downtime of the manufacturing lines, energy cost) while making them more efficient and limiting the risks of structural damage. The current sensors on the market are too restrictive on the conditions of use (temperature range, pressure, environment) and therefore do not meet the needs of manufacturers in the refractory concrete sector. Therefore, the objective of the European project named CUBISM, is to fill these gaps by proposing SAW-based pressure sensors capable of operating around 40 bars at much higher temperatures (about 500°C), in wider measurement ranges and in an environment compatible with that of refractory concretes. Developing these types of sensors consists on choosing the right piezoelectric materials, the optimal IDT (Inter Digital Transducer) configuration and the proper geometry that can withstand these hard conditions. The results obtained so far show a good pressure sensitivity and are the subject of this paper.

1. INTRODUCTION

Due to their small size and high sensitivity, surface acoustic waves (SAW) sensors are widely used not only in wireless communication systems [1] but also in all sorts of physical and biological applications [2]. These sensors offer the solution for sensing in harsh environments such as high temperature, humidity and pressure.

Reeder et al developed the first pressure sensor based on SAW in 1975 [3] using an electro-acoustical delay line fabricated on a ST-X quartz pressure dependent membrane. Since then, SAW pressure sensors were widely used in all scales of industrial applications going from monitoring pressure in tires [4] to offshore oil exploration [5].

In the case of refractory concretes, the optimization of drying times has indeed a significant economic impact (reduction of the downtime of production lines, energy cost...) while making them more efficient and limiting the risk of damage to structures. The availability of this physical data in real time via specific sensors integrated into the concrete is therefore a key to effective monitoring of the implementation cycle. The sensors currently on the market are too restrictive on the conditions of use (temperature range, pressure, environment) and therefore do not correspond to the needs of industrialists in the refractory concrete sector. Therefore, the objective of this work is to fill these gaps by proposing pressure sensors operating at much higher temperatures, in wider measurement ranges and in an environment compatible with that of refractory concretes.

2. SAW PRESSURE SENSOR FABRICATION

2.1 SAW resonator

The key component of a SAW resonator is the central interdigital transducer (IDT). An IDT consists of two comb-shaped metal electrodes that intersect with a strip overlap distance "W_a", where "a" is the strip width and "b" is the strip spacing (Fig.1). These strips are deposited on a piezoelectric substrate. The IDT period is defined as $p = a + b$. Where, a is the width of a strips and b is the spacing between two consecutive strips. When applying an AC voltage U between two strips, an accumulation of alternate charges occurs from one finger to the other thus creating an electric field between each pair of strips. The coupling of the electric field with the piezoelectric effect generates expansions and compressions thus creating vibrational displacements on the surface of the substrate.

This displacement creates a surface wave propagating perpendicular to the fingers.

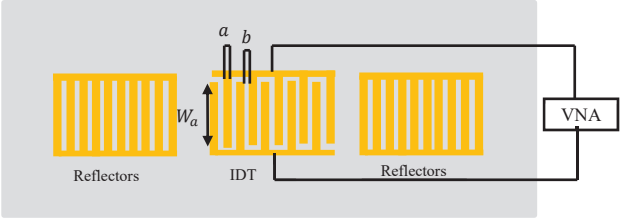


Figure 1. Schematic of a SAW resonator.

Therefore, a SAW resonator is the IDT (41 strips) placed between two reflectors (100 short circuited strips). The strip width a and spacing between two consecutive ones b are the same ($a = b = 8.8$ µm) which corresponds to a quarter of the wavelength λ. The reflectors are placed at ¾ p (maximum SAW reflection condition) from the on both sides of the IDT creating a resonance cavity. The electrodes are made of metal such as gold, aluminum and platinum. In the realization presented below, the electrodes of the SAW resonator are made of gold and 400 nm thick.

2.2 Dimensional optimization of the pressure sensor

The SAW resonator creates a resonating region on the surface of the piezoelectric substrate sealing the support's cavity; this substrate deforms due to the pressure applied uniformly on its surface. This deformation leads to stress on the surface causing a linear shift in the resonance frequency of the SAW resonators thus the possibility to monitor pressure in real time during a measurement cycle.

Optimizing the dimensions of a SAW pressure sensor is a key element so that the sensors can withstand the conditions where it is placed. In order to verify the limits of deformation of the diaphragm, ANSYS Workbench 16.0 finite element analysis (FEA) software to analyze the stress transferred to the diaphragm when subjected to pressures of up to 40 bar.

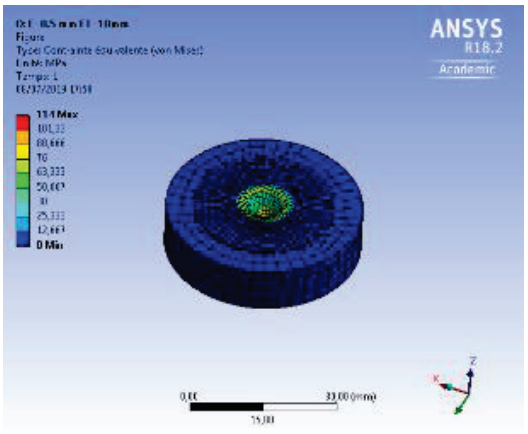


Figure 2. Modelling of the pressure sensor configuration.

The first simulations consist of lithium niobate (128° YX cut) diaphragm with 0.5mm thickness rigidly clamped on a ceramic support (to avoid thermal expansion) with a 10mm cavity on beneath. The simulation showed that this structure could maintain a pressure between 13–15 bars as shown in figure below. A crash test has been realized on a prototype and as predicted, the Lithium Niobate diaphragm fractured at precisely 13 bar with a 0.1 bar margin of error.

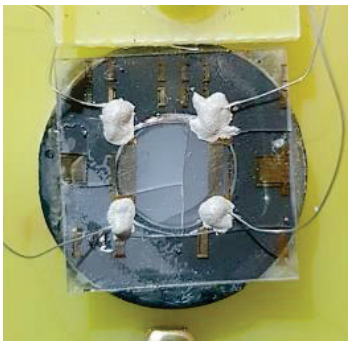


Figure 3. Crash testing of the pressure sensor prototype using 30 MHz SAW delay lines.

2.3 Characterization of the pressure sensor

The pressure sensors were tested in a Parr 4768 pressure vessel of 600 ml internal volume and 63.5 mm internal diameter (Fig. 4). This test chamber is capable to withstand pressure up to 130 bars. An external heating enables temperature tests up to 500°C. The pressure was provided by a N2 pressure cylinder (200 bar) connected to the vessel via a pressure regulator thus decreasing the pressure level down to 50 bars. An EquiLabo controller (Delta DTB4824 controller for pressure sensing and Delta DTB4848 for temperature regulation) was used to monitor internal pressure, to program temperature ramps and to monitor the temperature of the external heating system. The communication of the controller with the personal computer (PC) is effectuated via the Modbus protocol. The resonator's reflection coefficient S11 was measured with the HP4195A vector network analyzer (VNA). The frequency sweep span was set to 1 MHz, a polynomial fit procedure was applied in order to increase the precision of resonance frequency measurement. The communication of VNA with the PC is effectuated via a National Instruments GPIB-USB adapter. The internal vessel's temperature was additionally monitored with a thermocouple connected to a Keithley 2110 digital multi meter (DMM); the temperature measurement precision was 0.01°C. The communication of the DMM with the PC was effectuated via the standard USB connection. The whole setup is automatized and controlled with a MATLAB program running on the PC.

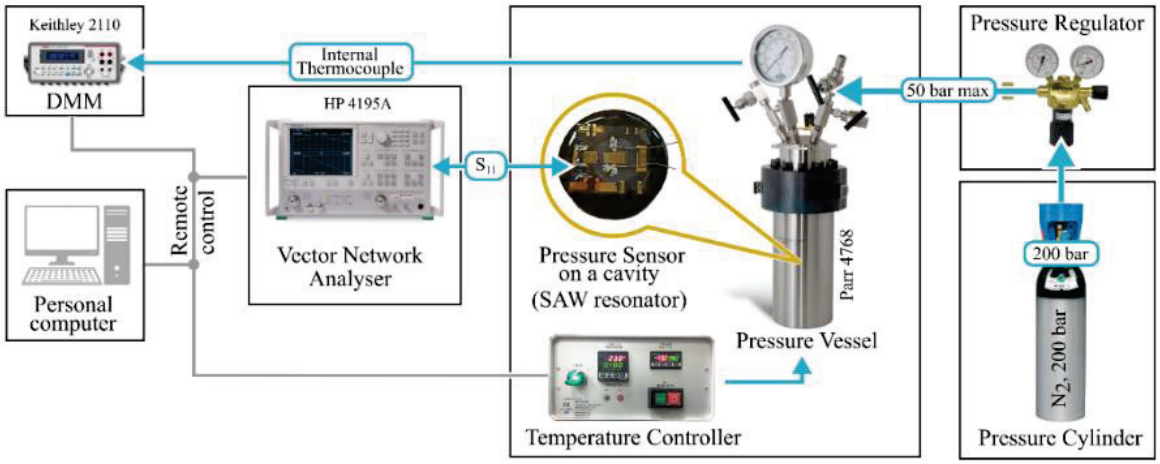


Figure 4. Schematic diagram of the pressure measurement system for the sensors.

3. RESULTS AND DISCUSSION

In order to study the SAW pressure sensors sensitivity range, the sensors were placed in the pressure vessel at constant temperatures. The first sensor was tested at room temperature in a range going from 0 to 12 bars. The gas was injected uniformly and pressure went up 1 bar per injection. The shift in the resonance frequency of the SAW resonator was recorded for every pressure level. As it shown in Fig. 5, the pressure sensor has a linear sensibility of 4.891 kHz/bar.

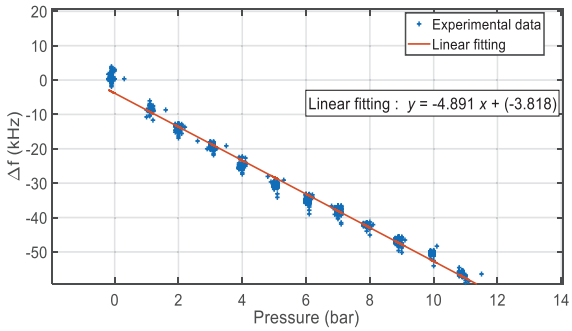


Figure 5. Frequency shift (Δf) vs pressure at ambient temperature.

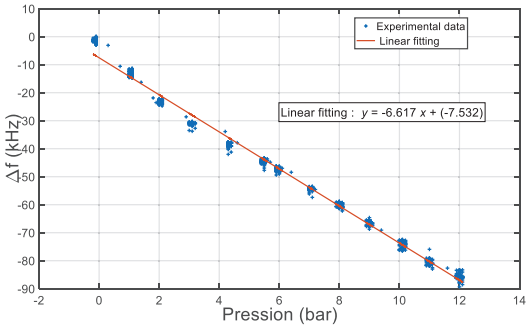


Figure 6. Frequency shift (Δf) vs pressure at 50°C.

As it shows in the figures above, the sensitivities of the SAW pressure sensors at different temperatures are of same order with a temperature factor yet to be calculated (Fig. 7).

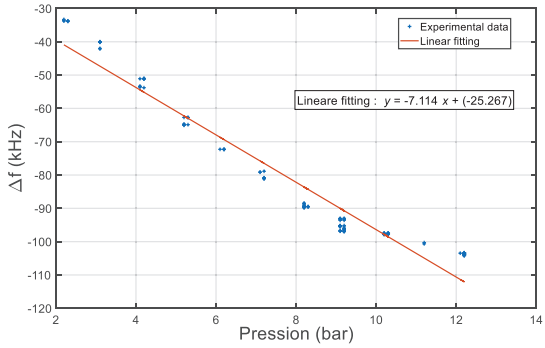


Figure 7. Frequency shift (Δf) vs pressure at 100°C.

As it shows in the figures above, the sensitivities of the SAW pressure sensors at different temperatures are of same order with a specific temperature factor at each temperature (Fig. 7).

4. CONCLUSION

The aim of this project is to develop a SAW pressure sensor capable of withstanding high pressures in a high temperature environments. The characterization of the first prototypes presented in this paper shows promising results to resolve the high temperature factor during the drying cycle of refractory concrete. Further prototypes are to be tested with different geometries, IDT's and piezoelectric materials to obtain maximum sensitivity.

5. REFERENCES

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