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Water pressure sensing based on wireless passive SAW technology

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Abstract

The conventional water pressure measurement method requires batteries as power sources for pressure sensors. This method is unreliable because the risk of damaging batteries is high especially in harsh environment. This paper provides a novel method that wireless passive surface acoustic wave (SAW) pressure sensor is introduced for water pressure measurement. Wireless passive SAW sensors do not need direct power supply. Therefore, batteries are not required by using this new technology. The main types of wireless passive SAW sensors are reviewed. The performance of wireless passive SAW sensor is tested. The water pressure sensing framework is proposed.

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Keywords: Water pressure; SAW sensor; reader; interrogation; response

1. Introduction

Water pressure measurement is of great importance for water supply, pipeline protection as well as leakage detection in urban water distribution networks. Time, terrain and behaviour of water consumers affect water pressure distribution in a place. In the recent studies, water pressure is measured by active (power supply is needed) pressure sensors. Both active sensor nodes and signal processing units with controllers are powered by limited life-time rechargeable batteries. Energy harvesting devices are developed for charging the batteries automatically from the surroundings. This current method is unreliable because the risk of damaging batteries is high especially in harsh environment e.g. extreme weather conditions. Also the energy harvesting devices connected with matching circuitry increase the system complexity and maintenance cost.

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In order to improve system reliability, reduce maintenance cost, alleviate power consumption and control sensor nodes to work smartly in water distribution networks, passive wireless SAW pressure sensors are nature devices for measuring water pressure because they do not need batteries (do not need direct power supply) and can be accessed and controlled wirelessly. Tang and Wu's (2014) previous work shortened the entire structure of the proposed water pressure measurement framework by using wireless passive SAW sensors instead of the battery needed active sensors. SAW sensor nodes only work when it is interrogated by the reader unit. Also benefiting from development of microelectronic fabrication technology producing small size SAW sensors, the sensor nodes could be deployed in a large scale along the pipeline.

Two main workhorses of SAW sensors in present industries – SAW Reflective Delay Line (RDL) sensor and SAW resonator sensor are reviewed and compared in Section 2. Then in Section 3, the selected wireless passive SAW sensor is tested, and the testing data are analysed for further research to use it on practical water pressure sensing system. The water pressure sensing framework is proposed in Section 4. Finally, the conclusions are given in Section 5.

2. SAW sensor

Lord Rayleigh (1885) found SAW propagating in semi-infinite isotropous materials. Then R. M. White and F. W. Voltmer (1965) successfully used Inter-Digital Transducer (IDT) deposited on piezo-crystals to excite and detect SAW. Since the advantages of SAW devices were discovered they had been applied to a variety of signal processing techniques including filtering, retardation, pulse compression, correlation, convolution etc. and in fields of radar, aerospace, radio and television, communication etc. In the early 90s SAW technology was introduced to design wireless passive sensors benefiting from the evolution of microelectronic technology. Wireless passive SAW sensors can be manufactured in large volumes by using semiconductor planar process.

Based on Morgan's (1991) study, SAW sensors consist of optically polished piezoelectric substrates or piezoelectric thin films applied to other types of substrates, upon which thin film conductive electrodes are patterned using photolithographic processes common to the semiconductor industry. The IDT configured by conductive thin-film electrodes is used to convert electrical signals to SAWs that propagate at the surface of the piezoelectric substrate. Also the IDT can be used to convert the SAW back to electrical signals.

The fundamental work principles of wireless passive SAW sensor consist of two main parts. The first part is the (Radio Frequency) RF signal interrogation and response. The reader unit emits high frequency pulse signal to the sensor. The antenna connected to IDT fabricated on the piezoelectric substrate receives and converts it to the SAW by IDT. The reflectors also fabricated on the substrate reflect the propagating SAW back to the IDT which can convert SAW back to RF signal and emitted by the antenna. The second part is the sensing principles. SAW is sensitive to the changed physical or chemical parameters because of its propagation properties, based on which high sensitivity sensor can be produced. When physical or chemical parameters acting on the surface of SAW device in different mechanisms, the disturbance can change the SAW propagation velocity and amplitude. Measurement can be achieved by measuring the corresponding changes in output signal (phase, frequency or amplitude).

Currently, the readers for exciting the wireless passive SAW sensors and receiving the response signals are designed based on two main mechanisms – one is time domain sampling, and the other one is frequency domain sampling. Two approaches were researched by previous scientists to implement the time domain sampling for the reader design. The first one is based on pulse radar, which uses switching devices to realise a simple diplexer. This method is normally used on fast moving objectives. But it is not widely applied because of the low duty cycle and the essential components fast sampling and signal processing devices are not economically efficient. The second approach is frequency–modulated radar. The application of (Time Bandwdith) TB products improves the duty cycle so the application range is enhanced. There are also two approaches to implement the frequency domain sampling for the reader design. The first one uses the structure of network analyser which reduces the usage amount of signal processing devices so the cost decreases. It also has relatively high duty cycle. However, this approach only suits slow moving objectives, and the diplexer can only be formed by one circle device or two separate antennas, which require the high dynamic range design for the reader. The second approach uses

Frequency Modulated Continuous Wave (FMCW) design. This method is similar to the aforementioned network analyser structure, but it can provide higher dynamic resolution. Therefore, frequency domain sampling is greater relied to design the reader of the wireless sensors. According to the European ISM band agreement, the two frequency ranges 433.0～434.77 MHz and 2.4～2.483 GHz are assigned for designing the reader of wireless passive SAW sensors.

2.1. SAW RDL

The SAW reflective delay line was introduced as wireless temperature sensor by X. Q. Bao et al. (1987). A major contribution to demonstration of capabilities of SAW RDL as automotive pressure, temperature, torque and road friction sensors was made in the 90s by L. Reindl et al. (1998), A. Pohl (1997) and F. Schmidt et al. (2001). Later the work was continued by X. Zhang et al.'s (2004) and T. L. Li et al.'s (2009) groups in China that also presented prototypes of RDL pressure and temperature sensors. Recently, SAW reflective delay line was used widespread as multi-functional wireless passive sensors.

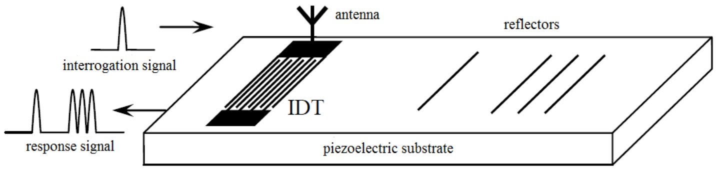

Fig. 1. The structure of a general SAW reflective delay line.

Showed in Fig. 1, antennas connected with the IDT of the SAW sensors allow wireless interrogation without the power supply from batteries. The SAW excited from the interrogation RF signals by the IDT and propagating on the surface of the piezoelectric substrate responds to variations in environmental physical or chemical conditions such as temperature, pressure, strain, gas density, humidity, acceleration etc. In addition, each SAW RDL sensor can be designed to provide a unique ID through coding, frequency multiplexing, time division or a combination of these techniques, based on which the simultaneous interrogation of multiple devices can be achieved as indicated by M. Pereira da Cunha (2011).

Lamothe et al. (2012) indicated the basic operation principles of SAW RDL sensors with RFID tags. The reader unit sends an interrogation signal which provides energy to excite a passive sensor. The IDT fabricated on the sensor substrate can convert electric energy into mechanical energy of SAW. The sensor architecture builds a response in form of reflected acoustic signal which contains information such as a unique identification number and/or a measured physical/chemical quantity. Propagating back to the IDT, this acoustic response is converted back into an electric signal sent by the same antenna (monostatic configuration) to the reader unit where the information is deciphered.

2.2. SAW resonator

SAW resonators were developed as wireless strain and torque sensors on rotating shafts by A. Lonsdale and B. Lonsdale (1991), and then SAW resonator torque sensors were also demonstrated by Baldauf and Schrufer (1992). From 1992 to 1997, Buff and his group made great contribution to the development of wireless SAW resonator sensors. They used three SAW resonators for simultaneous measurement of both temperature and pressure for car tyres. Then V. Kalinin et al. (2001) and B. Dixon et al. (2006) from Transense Technologies plc in the UK developed the industrialized tire pressure monitoring system (TPMS) from 2001 to 2006. Later, Lardat et al. (2006) proposed a wafer-scale all-quartz package design for a similar resonant TPMS sensor.

Showed in Fig. 2, the fundamental type of SAW resonator sensor consists of piezoelectric substrate, IDT and Bragg reflectors. Bragg reflectors are formed by regular arranged metal straps. Every strap reflects only a small quantity of SAW. The superposition of the SAW reflected by the repeated regular arranged metal straps allows frequency selection of different reflected SAW frequencies. Reflected signals with identical frequency could be summated. The reflector arrays on both left and right sides of the IDT form the resonant cavity. IDT is designed based on SAW resonator centre frequency and allows the acoustic-electromagnetic coupling of the SAW and electric signal. When external disturbance changes either the size of the resonator or the propagation speed of SAW, the centre frequency of the SAW resonator will be changed subsequently. Measurement could be achieved by detecting such changes from the response RF signals.

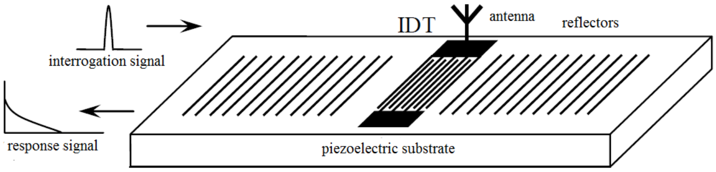

Fig. 2. The structure of a general SAW resonator sensor.

2.3. Comparison between SAW RDL & resonator

Table 1 shows the comparison between SAW RDL and SAW resonator. An important advantage of SAW RDL sensors over SAW resonator sensors is the possibility to build a multi-sensor collisionless system using TDMA by J. H. Kuypers et al. (2006), CDMA by E. Dudzik et al. (2008) and orthogonal frequency coding (OFC) principles by D. C. Malocha et al. (2008). Hence embedded IDs can be provided by using OFC principles. However, SAW Resonator sensors have a larger Q factor that potentially ensures a higher resolution of the wireless measurement system indicated by V. Kalinin (2004). They allow faster interrogation with the period well below 1 ms (interrogation of RDL sensors by a FMCW signal giving comparable resolution takes tens of milliseconds indicated by S. Scheiblhoher (2009)). SAW RDL sensors decipher information by time delays or phase changes compared with original interrogation signals, while SAW resonator sensors decipher information by obtaining resonant frequency from the response signal. SAW RDL can be more easily used as a platform to constitute multifunctional sensors than SAW resonator (limited by its fundamental structure).

Table 1. Comparison between SAW RDL and SAW resonator.

	SAW RDL	SAW resonator
Embedded ID	Yes	No
Resolution	Lower	Higher
Interrogation period	Several tens ms	Below 1 ms
Signal processing	Decipher information by time delays or phase changes compared with original interrogation signals	Decipher information by obtaining resonant frequency from the response signal
Application range	Wide	Narrower than SAW RDL

3. Test experiment and analysis

For water pressure sensing, IDs are important to locate each sensor node. The difference of interrogation period between these two types of wireless passive SAW sensors has little impact on practical water pressure sensing. Hence, SAW RDL sensor is selected to measure water pressure in this case.

3.1. Structure of the selected SAW RDL sensor

Fig. 3 shows the structure of the selected SAW RDL sensor. Three reflectors are deposited on the two sides of the IDT. When SAW generated by the IDT in the middle propagates to two opposite directions, reflectors on both sides can reflect it back to the IDT. This structure can effectively promote the response signal strength compared to the one side SAW RDL structure.

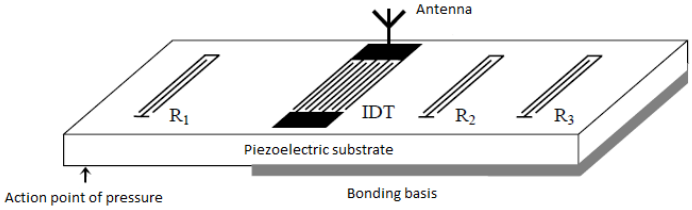

Fig. 3. The structure of the selected SAW RDL sensor.

Action point of pressure is on the left side of the sensor. Hence, pressure is related to the response signal generated from reflector 1. On the right side of the sensor, the piezoelectric substrate is bonded to the sensor metal package. Therefore, the response signal generated from reflector 2 and 3 can be used to decipher the temperature. In addition, the response signal generated from reflector 2 is also used to compensate the temperature influence to the pressure measurement.

3.2. Experiment

Fig. 4 shows the experiment instruments. Agilent E4438C ESG Vector Signal Generator and Agilent 33220A Function/Arbitrary Waveform Generator are used to generate modulated pulse signal as the interrogation signal for the SAW RDL sensor. The carrier signal is the standard sine wave which is generated by Agilent 33220A Function/Arbitrary Waveform Generator. The baseband signal is 30 µs period pulse signal which is generated by Agilent E4438C ESG Vector Signal Generator. The interrogation modulated pulse signal can be generated by implementing Amplitude-shift Keying (ASK) on these two signals. Agilent E4440A PSA Series Spectrum Analyser is used to verify the centre frequency of the output signal from the signal generator. And Agilent MSO 6104A Mixed Signal Oscilloscope is used to receive and analyse the interrogation and response signal. 433 MHz antenna is used to emit and receive the wireless RF signals.

Fig. 4. Experiment instruments.

Fig. 5 shows the selected SAW RDL sensor used in this test. Two 433 MHz coil helical antennas are connected to the SAW RDL sensor to constitute dipole antenna. The whole internal sensor structure is packaged in a hermetically sealed metal cover in order to shield the external electromagnetic interferences. The rated pressure range of this selected sensor is 0 ~ 1.5 MPa, which meets the general water pressure sensing requirement.

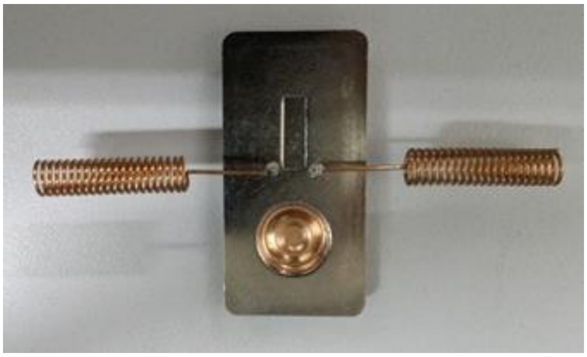

Fig. 5. The SAW RDL sensor with antennas.

3.3. Testing data analysis

Fig. 6 shows the influence of carrier wave frequency on response signal amplitude. Only when the carrier wave frequency is 425 MHz, all response signal 1, 2 and 3 can reach relatively high amplitude. Therefore, the further experiment should be implemented under the carrier wave frequency of 425 MHz which is around the resonant frequency of the selected SAW RDL sensor.

Fig. 7 shows the influence of interrogation pulse width on response signal. The signal quality increases with the increase of the pulse width. The widths of response signal 1, 2 and 3 increases (the interval widths between response signal 1 and 2, 2 and 3 decreases) with the increase of the pulse width. When the pulse width is greater than 1000 ns, the intervals between response signal 1 and 2, 2 and 3 are too narrow to be clearly distinguished. Therefore, the further experiment should be implemented under the interrogation pulse width of 1000 ns.

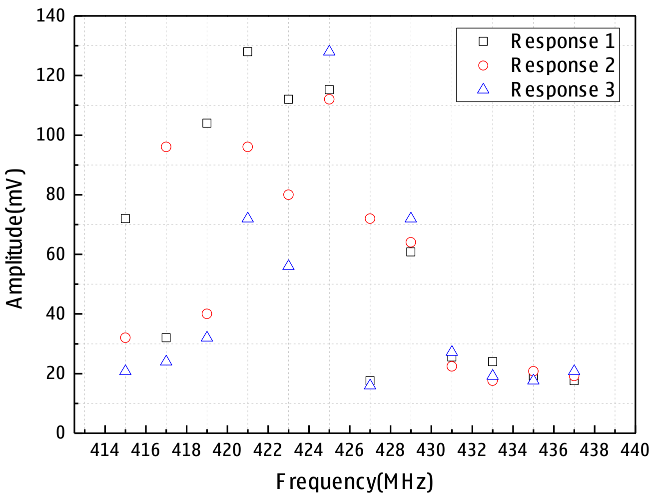

Fig. 6. The influence of carrier wave frequency on response signal amplitude.

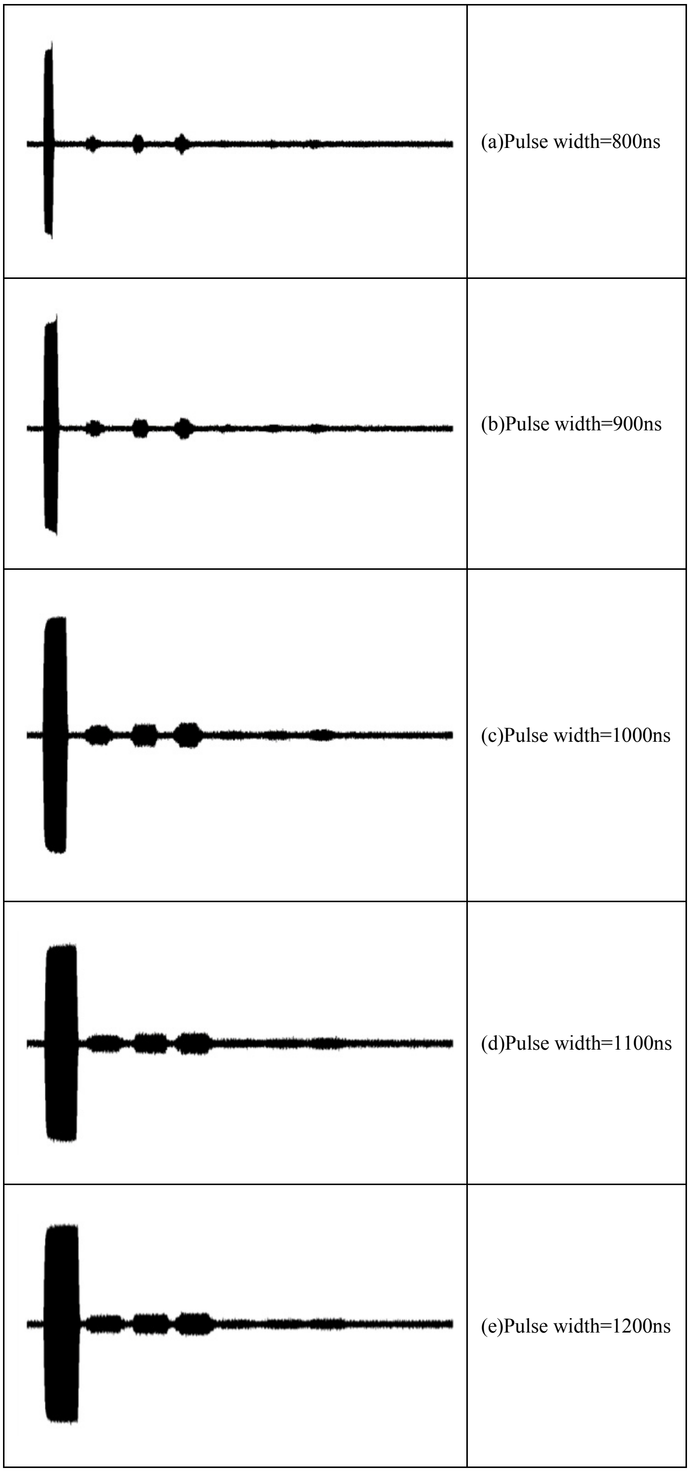

Fig. 7. The influence of interrogation pulse width on response signal.

The signal generators and the oscilloscope used in this test simulate the function of the reader, in order to find the most appropriate parameters to design the reader. Through the initial test of the selected sensor, the best interrogation signal frequency 425 MHz is confirmed, and the best pulse width of the interrogation signal 1000 ns is evaluated. Therefore, the reader should be designed based on these results.

4. Water pressure sensing

Plessky et al.'s (2010) research indicated that the reading range between SAW sensors and the reader could be up to 10m with radiated emanation (EM) power of only around 10mW in a frequency bands 200MHz to 400 MHz. Therefore, one reader can read and interrogate a significant area of SAW sensors in the open space. Considering the underground environment, the reading range will be shortened but still significant in our studies. The water pipes should not be metal in this case.

Showed in Fig. 8, the adaptor is developed to measure the water pressure from the air pressure using the wireless passive SAW pressure sensor in the PVC pipe. It is noted that the wireless passive SAW pressure sensor works without contacting the water. The SAW sensor node can be excited when receiving an interrogation signal from the reader unit, and then a response signal including sensing information can be transmitted back to the reader and deciphered.

The sensor node in the PVC pipe is powered up by the interrogation signal from the reader unit, which acts as a passive load. Therefore, the batteries are not required to supply the power for the sensor nodes. Hence, the maintenance cost and energy consumption could be reduced significantly.

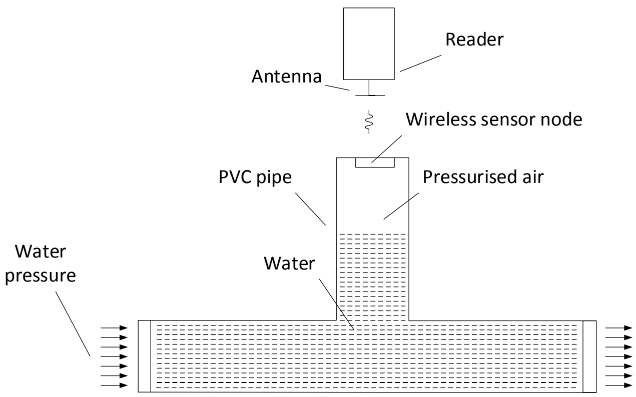

Fig. 8. The adaptor designed to use the wireless passive SAW sensor for water pressure measurement

5. Conclusion

The problems in previous water pressure sensing system have been discussed. Two main types of wireless passive SAW sensors – SAW RDL sensor and SAW resonator sensor have been reviewed and compared for choosing a better type for water pressure sensing. Through testing the selected SAW RDL sensor, the best interrogation signal frequency 425 MHz is confirmed, and the best pulse width of the interrogation signal 1000 ns is evaluated for reader design. A novel adaptor for water pressure sensing has been designed. By applying wireless passive SAW technology energy efficiency and reliability can be enchanced, maintenance cost can be significantly reduced because batteries are no longer required.

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