Torsional Acoustic Waveguide Sensor for Temperature and Liquid Level

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Abstract — In the present work a novel intrusive torsional acoustic waveguide sensor for temperature (T) and liquid level (H), which are critical measurands in process control systems, is developed. This sensor essentially consists of a metallic waveguide of varying cross section in which torsional acoustic waves are excited and received by a single piezoelectric transducer. The changes in the time of flight of the excited torsional acoustic waves in the waveguide are shown to directly relate to temperature and liquid level in the probed media. Experimental measurements showed that the flight time increases with temperature up to 1000°K while the resolution for liquid level was about 0.3 mm which is significantly less than industry standards of 1.5 mm.

Keywords - Ultrasonic Sensor; Process Control; Liquid Level; Torsional Interface Echo; Hostile Environment

I. INTRODUCTION

The sensing of temperature (T) and liquid level (H) in hostile environments such as high temperature and aggressive liquids poses significant challenges. First, the materials used in the T and H sensor must be able to survive in this environment. Secondly, the probing mechanism inherent in the sensor must be able to interact with the hostile environment in a friendly fashion. Many of the T and H sensors use probing mechanisms such as electromagnetic fields, light, resistance, electric current or acoustic waves, each of which have both advantages and disadvantages. In many hostile media one would ideally like to excite and receive energy external to the region being probed. Acoustic waves offer an interesting approach to achieve this objective.

The most common acoustic wave which has been utilized in acoustic wave sensors is the bulk acoustic wave (BAW) which is typically excited and received using piezoelectric, magnetostrictive or electromagnetic acoustic transducer (EMAT) technology [1]. This type of sensor has found application in diverse areas such as non-destructive testing (NDT), the sensing of T, H, density and viscosity, the curing of epoxy, and the settling of concrete and flow front monitoring [2]. An acoustic wave which has received much less attention is the torsional acoustic wave [3, 4]. This wave can be remotely excited and received in an arbitrary structure or waveguide which can be used as a probe or sensor. Additionally, in contrast to BAWs, the energy associated with a torsional acoustic wave is concentrated near the surface which allows it to be very sensitive to the measurands of interest.

In the present work a single piezoelectric shear transducer is used to launch and receive torsional acoustic waves in a wave guide structure thereby forming a torsional acoustic wave guide sensor. In order to demonstrate the applicability of this novel type of sensor, experiments are performed to detect T and H in both air and liquid environments.

II. TORSIONAL ACOUSTIC WAVEGUIDE SENSOR

The Torsional Acoustic Waveguide (TAW) sensor used in the present work is shown in figure 1. The waveguide is made of elastic materials which consist of lead-in and sensing zones. Torsional acoustic waves are excited by a piezoelectric shear transducer located at the free end of the lead-in waveguide. The transducer is coupled with a dummy transducer made from materials to create an equivalent mass. This couple generates the torsional waves. In monitoring temperature the excited torsional acoustic wave travels down the lead-in waveguide and reflects at the interface of the lead-in section and sensing zone and at the free end of the sensing zone. In the case of liquid level monitoring an additional reflection at the liquid surface occurs. The flight times associated with the two reflections are used as the probing mechanisms of the sensor. The lead-in section is circular in cross section and acoustically slender. This means that the lead-in section diameter is less than the wavelength of the torsional acoustic wave, ensuring that the acoustic waves are not significantly dispersed. The lead-in section allows the signal generated from the transducer to enter the sensing zone with minimal noise. Typical dimensions of the lead-in diameter range from 0.5 mm to 25.4 mm and the lead-in length is approximately 300 mm. The sensing zone of the waveguide follows the lead-in section. It is of a different cross section than the lead-in but is made of the

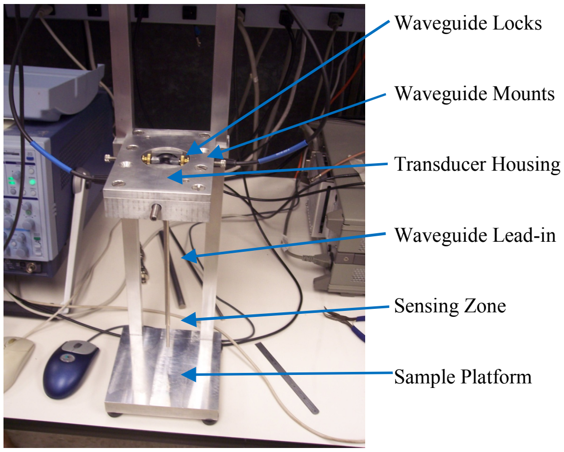

Figure 1a – Figure of the actual TAW sensor integrated onto the waveguide stand

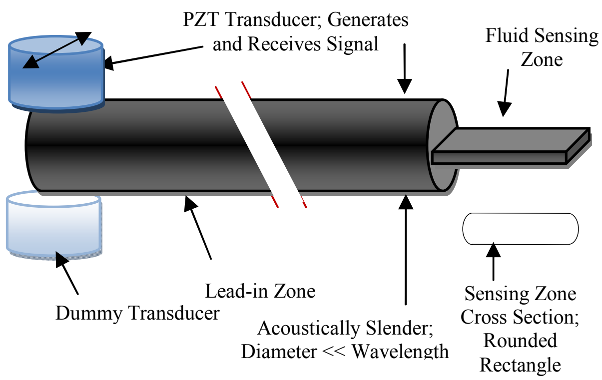

Figure 1b – Pulse-echo waveguide sensor configuration using one TSM (Thickness Shear Mode) transducer coupled tangentially to the end of the lead-in waveguide.

same material. This zone is inserted into the media of interest for sensing. Various geometrically shaped sensing zones offer advantages over others, depending on the application. Typically the sensing zone length is about 50 mm and the cross sectional geometry may vary from circular to rectangular. Our research used a rounded rectangule cross section as seen in figure 1b.

The TAW sensor differs from earlier torsional sensors in that it utilizes a piezoelectric shear transducer to excite and receive torsional waves whereas earlier sensors used magnetostriction to generate acoustic waves. Piezoelectric transducers have two important advantages over magnetostrictive types: (1) They are readily available from several manufacturers; (2) they may be clamped onto virtually any elastic waveguide material. The excited shear NDT-style contact transducer generates a displacement which impulsively twists the guide, launching the torsional wave. Echoes are detected by the same transducer.

The sensor uses the flight time between the echoes to perform the detection. Changes in temperature or fluid properties surrounding the sensor cause an increase or reduction in flight time which is used to determine the specific measurand. In the temperature measurement, the overall length of the waveguide changes with temperature due to the thermoelastic properties of the waveguide material. This causes a corresponding change in the travel time of the torsional acoustic wave. When the TAW sensor is used for liquid measurement, the mass loading of the liquid on the waveguide is the predominant effect. In particular liquid mass loading reduces the speed of the torsional acoustic wave in proportion to the liquid density. The sensing zone geometry and/or material can also play a role in the speed reduction. By measuring the change in flight times one can accurately extrapolate measurands of the media the sensor is immersed in such as liquid level, viscosity etc.

III. EXPERIMENT

The present study used three materials common to the process control industry, 6061-T6 Aluminum (Al), 316 Stainless Steel (SS), and Commercially Pure (CP) Titanium (Ti). The lead-in waveguide was 304.8 mm in length and 6.4 mm in diameter. The sensing zone was 50.8 mm in length and had a rectangular cross section, 6.4 mm wide and 2 mm high, chosen for its sensitivity and ease of manufacture compared to other cross sections. The transducer used to excite the torsional acoustic wave was a lead zirconium titanate (PZT) shear transducer. To generate and receive the torsional acoustic waves, a RITEC RAM-5000 tone burst generator was used. Once the signal is generated, the transducers detect the reflections in the sensing zone of the guide and send the signal to a oscilloscope for processing. The oscilloscope reads the flight times of the sensor down to nanosecond precision as shown in figure 2. Once flight times are known, computer programs in MATLAB are used to correlate the change in flight times to the measurand of interest.

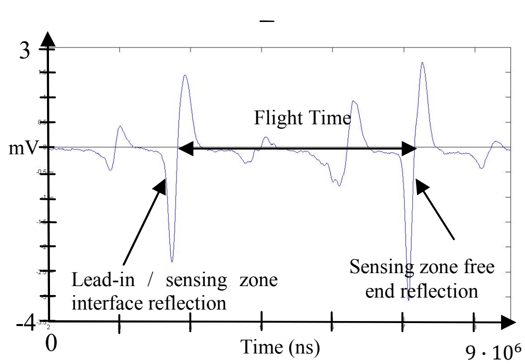

Figure 2 – Sample reflections from TAW sensor in air

It was found that the pulse-echo layout yielded a standard deviation between flight times of 1.68 ns and an SNR / IL of 0.39. This method gives results similar to those obtained using two transducers [3, 4].

IV. TEMPERATURE

The TAW sensor was used to monitor temperature, a critical parameter in many process control applications. Initially two thermocouple (TCs) were placed in the TAW sensor to ensure an accurate measurement of temperature. One was placed in the center of the test chamber free from contact with the sensor and another was placed axially inside the sensor zone. An examination of the reflection coefficient as a function of hole diameter was performed to determine the largest hole that could be drilled into the sensing zone without interfering with the echoes [5, 6].

Examining figure 3 it is observed that a hole may be drilled up to approximately 1.25 mm in diameter without interfering with the reflection echo coefficients by more than 5%. Therefore a TC was placed axially at the lead-in sensing zone interface.

The sensor was placed inside the environmental chamber with the axially placed TC in the sensing zone. The sensing zone was completely immersed in the chamber with the lead-in insulated from heating with foam insulation around the chamber insertion point. Torsional acoustic waves were excited from the RITEC tone burst generator and flight times were recorded with an oscilloscope. Heat was gradually increased so that 20 sample points were taken for each TAW sensor material. Each data point was taken when both the TC inside the TAW sensor and the TC free in the chamber recorded the same temperature. The flight times as measured between lead-in / sensing zone interface and the echo from the sensing zone free end, were normalized with respect to room temperature flight time for each sensor material. Figure 4 presents the experimentally observed normalized flight times for 316SS, 6061-T6 Al, and CP Ti as a function of temperature up to 1000°K.

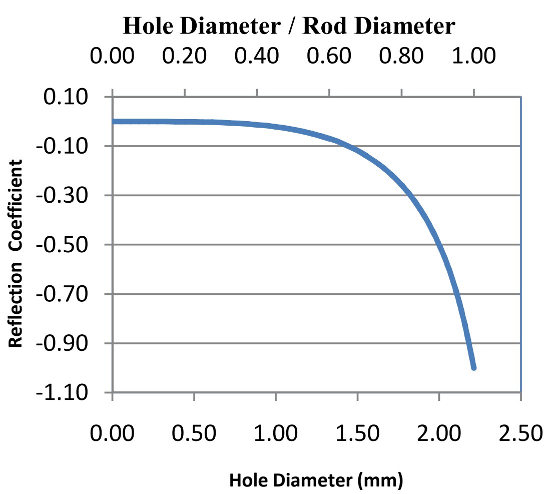

Figure 3 – Reflection coefficient vs hole diameter / rod diameter and hole diameter

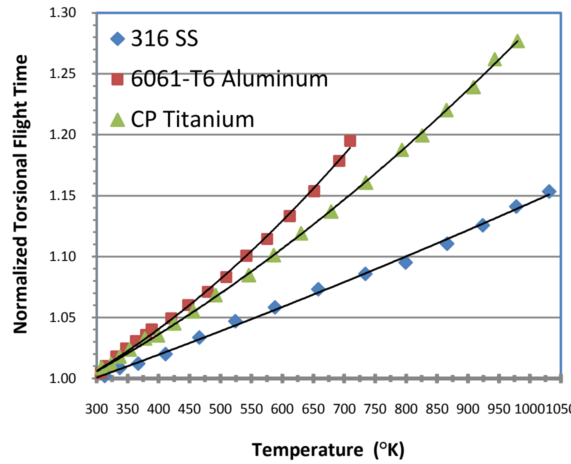

Figure 4 – Normalized torsional flight time vs. temperature

It was observed that each metal followed an approximately linear change in flight time in response to an increase in temperature [7]. Tests showed an approximate resolution of 0.07°C. To authenticate the validity of the results, a comparison was made to the shear modulus, G, values which can be determined from the experimental results. Since G is a function of the wave speed, c, and density of the waveguide material, one can use the flight time with the known sensor length to determine c, and calculate the shear modulus. The G values obtained in the present experiment are compared to literature values for G in figure 5. It can be seen from figure 5 that agreement is very good.

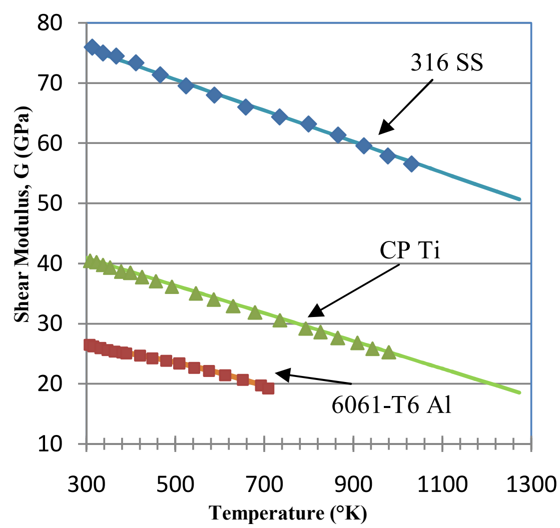

Figure 5 – G from the literature [7] vs. G from present work. Solid lines: literature. Data points: present experiments

V. Liquid Level

The current research also sought to improve the measurement of liquid level in hostile environments such as those associated with aggressive semiconducting liquids. When measuring liquid level, the primary factor that increases flight time is liquid mass loading. The density of the surrounding medium causes a reduction in torsional acoustic wave speed that is proportional to how far the sensor zone is immersed in the liquid. This mass loading results in an increase in flight time [8]. Unique to liquid level measurements is the generation of another echo at the interface where the gas, normally air, and liquid meet in the sensing zone. The change in liquid density from gas to the liquid changes the torsional wave impedance giving rise to the interface echo. Because the wave impedance change may be small, the interface echo is much smaller the end-echo. This in turn makes the measurement of flight times from the interface echo, and hence the measurement of liquid level, challenging. What makes the challenge of measuring the interface echo appealing however is the accuracy that can be obtained. Preliminary research in the TAW sensor has shown an echo resolution of $\pm$0.37 ns, which corresponds to a liquid level measurement accuracy of 0.28 mm, a large improvement over the 1.5 mm requirement set by industry [3]. To ensure maximum accuracy within the TAW sensor both end and interface echoes are used as an internal crosscheck.

Fluid level determined from an interface echo avoids the earlier problems found in industry liquid level sensors where bubble nucleation on the sensor resulted in inaccurate measurements. Specific applications where this occurred were nuclear power plants, liquid level within aircraft fuel tanks or wastewater tanks at any altitude [8]. Since the interface echo occurs directly at the gas / liquid location, bubble nucleation does not affect measurement accuracy.

For the given liquid level test, the sensing waveguide with a rectangular cross section, aspect ratio 3, was immersed in tap water in 5 mm increments. Industry standards state that most

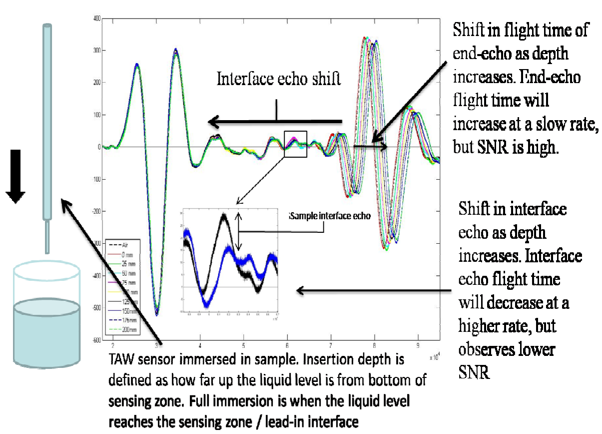

Figure 6 – Liquid level experiment process; interface echo and end echo

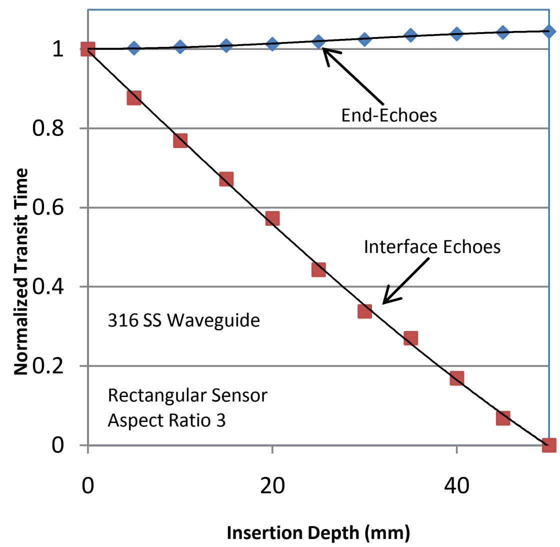

Figure 7 – Normalized interface and end-echo torsional transit times vs. insertion depth

liquid level sensors need to be made from 316SS. This is due to the fact that the anti corrosive properties of 316SS protect the liquid from contamination. Therefore 316SS was chosen as the sensor material. Flight times normalized to room temperature and with no mass loading were recorded at each immersion depth.

Results for the liquid level test are shown in figure 5, depicting both end-echo and interface echo normalized flight times. Flight times measured from the lead-in / sensing zone interface to the sensing zone free end, referred to as end-echoes, showed an increase of approximately 46.08 ns/mm. Flight times measured from the lead-in / sensing zone interface to the reflection generated at the gas / air interface, referred to as the interface echo, exhibited a decrease in flight time of 1034.96 ns/mm. The interface echoes flight time changes on the order of 20 times more per mm than the end echo. This makes it a more sensitive and attractive measurand to use for liquid level measurement.

VI. Conclusions

A single transducer TAW sensor was developed for measurement of T and H with a resolution in the nanosecond range or less. This approach offers an advantage over other ultrasonic sensing devices by using half the transducers to generate and receive its signal, thus reducing cost while still demonstrating high sensing resolution. A temperature calibration was performed with various TAW sensors up to 1000°K. The test showed agreement within 2% between shear modulus valued calculated from the temperature experiment and those found in literature. With the sensors demonstrated resolution, the present results show a temperature resolution of ±0.05°C.

A liquid level test was performed using a single material, 316 SS, due to the fact that other metals are not allowed in many liquid level applications due to material break down and contamination. Both the end-echo and interface echo were measured when being immersed in tap water from 0 to 50.8 mm. End-echo flight time showed an increase of approximately 46.08 ns/mm, while interface echo flight times exhibit a decrease in flight time of 1034.96 ns/mm. Approximate sensor accuracy for liquid level measurements is shown to be 0.28 mm.

The TAW sensor offers highly accurate real time temperature measurement using a novel torsional ultrasonic method. Ultrasonic temperature measuring has advantages over previous resistance based methods in that it has a higher sensing resolution, is unaffected by microwave signals or outside electrical interferences and can operate through a much more hostile range of situations due to its durable design. What gives the TAW sensor a large advantage is that it is not limited to one measurand for sensing. The unique sensing zone design allows it to be expanded to detect multiple measurands at once. Liquid level has been investigated and it is seen that the sensor is able to read changes in liquid level using interface echoes with high precision. Long range the sensor may be improved and expanded to simultaneously measure other process control measurands that are critical to industry such as density, viscosity, or fluid flow. Combining all of these with one low cost, accurate and reliable sensor would create a valuable product to process control applications.

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