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ULTRASONIC WAVEGUIDE BASED LEVEL MEASUREMENT USING FUNDAMENTAL GUIDED WAVE MODE L(0,1) T(0,1) AND F(1,1) SIMULTANEOUSLY

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ABSTRACT

This paper reports an ultrasonic waveguide sensor for liquid level measurements using three guided wave modes Longitudinal L(0,1), Torsional T(0,1) and Flexural(1,1) simultaneously. These wave modes were simultaneously transmitted/received in a thin stainless-steel wire-like waveguide using a standard shear wave transducer. Experiments were conducted in non-viscous fluid (water) and viscous fluid (castor oil). It was observed that the flexural F(1,1) wave mode showed a change in both time of flight (due to change in velocity and dispersion effects) and amplitude (due to leakage) for different levels (0-9cm) of immersion of the waveguide in a fluid media. For the same level of immersion, the L(0,1) and the T(0,1) modes show only relatively smaller change in amplitude and no change in time of flight were observed. The experimental results were validated using Finite Element Model (FEM) studies. Also, by monitoring all three wave modes simultaneously, a more versatile and redundancy in measurements of the fluid level inside critical enclosures of processing industries can be achieved by compensating for changes in the fluid temperature using one mode while the level is measured using another. This ultrasonic waveguide technique will be helpful for remote measurements in physically inaccessible areas and in hostile environments.

Keywords: Guided wave, Level measurement, waveguide sensors.

TABLE 1 WAVEGUIDE DETAILS

Material	SS-308L
Mass density (ρ) - kg/m^3	7950
Young's modulus (E) GPa	183
Poisson's ratio (μ)	0.3
Waveguide Diameter (D) mm	1

1. INTRODUCTION

The measurement of liquid level in industries (oil, petrochemical, etc.) is essential during process monitoring and custody transfer. Typically, in industries, two types of liquid level measurement techniques were reported namely, (a) invasive (contact type) and (b) non-invasive (non-contact type)[1]. In an invasive type of liquid level measurement concept, the sensor shall be in contact with the liquid or embedded in it, for example, floats, dip probes etc. The non-invasive techniques (acoustic sensors, ultrasonic and optical sensing methods) are widely used in specific applications which involve more safety requirements in the hazardous/ inaccessible region of interest[1-5]. Different ultrasonic waveguide sensors (contact type) have been reported [1-10] in a wide range of applications, and also these sensors are capable of providing accurate measurements of the properties of the surrounding medium that include temperature, fluid level, rheological properties, cure monitoring etc.

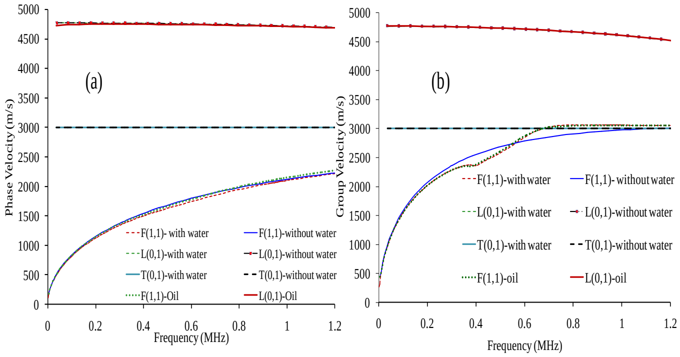

FIGURE 1: DISPERSION CURVES FOR 1MM STAINLESS STEEL WAVEGUIDE; (a) PHASE VELOCITY AND (b) GROUP VELOCITY (VG).

Lynnworth et al.[1] have extensively reported on the fluid level, temperature and flow of fluid measurement concepts using ultrasonic waveguide techniques. Later, different waveguide configurations were developed by different authors for fluid

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level sensing. Flexural wave modes inside a waveguide are expected to be more sensitive to fluid loading, as compared to the longitudinal and torsional wave modes, due to the out-of-plane displacement components, which leads to high rate of wave energy leakage from the waveguide surface into the fluid medium. Recently, the transverse pulse train technique[11] was demonstrated for measuring the liquid surface level using flexural wave on a pipe waveguide. Knowles[12] studied the excitation and propagation of flexural waves to detect the surface level of an aerated fluid using high-frequency pulse train technique. In this work, we are interested in the development of a contact type waveguide sensor for the level measurement of viscous and non-viscous fluids based on the changes in the behavior of F(1,1) wave modes, using a single shear transducer. The transducer is rigidly fixed on the surface of the thin circular waveguide to transmit/receive F(1,1) wave modes in a pulse-echo modality. These wave modes are explored for measurement of level of fluids, and the sensitivity of these wave modes are also studied.

2. WAVEGUIDE SENSOR SETUP

A thin stainless steel (SS) waveguide was selected in this work. The waveguide dimensions and material properties are given in Table 1, and the theoretically obtained dispersion curves and attenuation plot using Disperse software[13] is shown in Fig. 1.The Particle displacements can reveal the characteristic behaviour on the surface of the waveguide material that makes them useful for measuring the fluid properties. Where, F(1,1) mode shape shows that all three displacement components (Axial (Uz), Radial (Ur) and Angular (Uq)) on the surface of the waveguide are maximum, which makes it sensitive towards the shear properties. In the case of L(0,1) mode, the axial displacement (Uz) is more dominant than the radial displacement (Ur) and can be used to measure the fluid properties like density and bulk modulus. Similarly, T(0,1) mode shape shows displacements in the angular direction only and it is suitable for measurement of the shear properties of the fluid.

An operational frequency of 500 kHz was preferred in this work in order to limit the level of dispersion (Refer Fig 1) A conventional shear transducer with a bandwidth of 250kHz-620kHz was coupled to the waveguide using a very thin layer of viscous silicone based ultrasonic couplant and constant pressure on the surface of the waveguide. The transducer was oriented at an angle of 45° to the axis of the cylindrical waveguide as shown in Fig. 2(a) for simultaneous transmission/reception of L(0,1), T(0,1)[10] and F(1,1) wave modes, and the obtained A-scan signal is shown in Fig. 2 (b).

3. RESULTS AND DISCUSSION

The liquid level sensing was based on the measurement of ultrasonic wave behavior in the straight waveguide configuration. The schematic of the experimental setup is shown in Figure 3. The waveguide was positioned vertically in the container for level measurement experiments. The reference level scale was marked on the test beaker. One end of the waveguide was connected to the shear transducer and the other end of the waveguide was immersed inside the liquid for level measurement. The initial A-scan signal was obtained when the waveguide was not subjected to fluid loading (air medium, i.e., 0-cm) as shown in Fig. 2 (b) and subsequently, the fluid (water) was filled gently in the cylindrical container with an increment of 10 mm. The A-scan signals were acquired at each 10 mm interval while filling 90 mm depth of water in the beaker and the acquired corresponding A-scan signals are shown in Fig. 4. While monitoring the signals for the F(1,1) modes, it was very critical to extract the change in time-of-flight (δTOF) and peak amplitude information from the A-Scan signals using peak tracking concept[10].

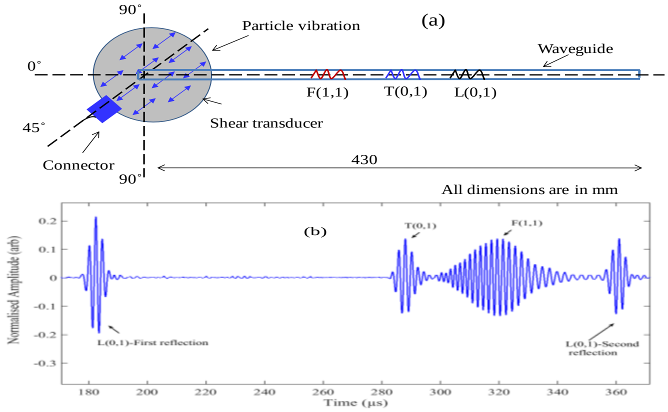

FIGURE 2: (a) SHOWS THE ORIENTATION (45º) BETWEEN THE WAVEGUIDE AND SHEAR TRANSDUCER, (B) L(0,1), T(0,1) AND F(1,1) WAVE MODE REFLECTED SIGNALS EXPERIMENTALLY OBSERVED FROM THE WAVEGUIDE (IN AIR MEDIUM).

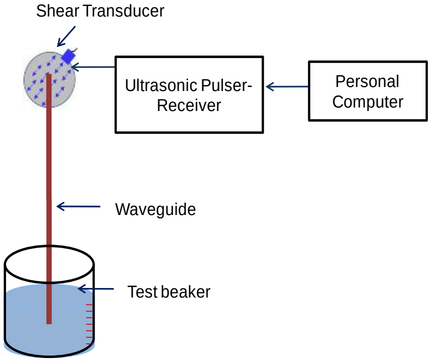

FIGURE 3: SCHEMATIC OF THE EXPERIMENTAL SETUP FOR LIQUID LEVEL MEASUREMENT USING A SINGLE WAVEGUIDE.

Here, Significant change in amplitude were observed for all three wave modes(L(0,1), T(0,1), and F(1,1)) also a significant change in time of flight (δTOF) of the F(1,1) signal were observed at every 10 mm increment of fluid loading as shown in figure 5. The water level was measured by monitoring the change in amplitude as well as the change in time of flight (δTOF) from the obtained A-scan signals. Experiments were repeatedfor few trials, and it was observed when the sensor was exposed to different water levels the sensitivity of the peak amplitude feature was significantly higher in flexural wave mode F(1,1) as compared to the other two wave modes (L(0,1) and T(0,1)). The time of flight of the

F(1,1) was also found to be sensitive to the fluid level indicating that the group velocity of the F(1,1) mode has a high dependency on the fluid level while the other modes did not indicate any measurable change in the time of flight

Figure 5 shows the δTOF effect on the F(1,1) wave modes, when the sensor was immersed in different levels on water and castor oil. It can be observed that the F(1,1) mode is relatively more dispersive compared to the T(0,1) and L(0,1) modes in the range of frequencies considered here i.e., 450-550 kHz (Refer figure 1). The F(1,1) mode leakage (attenuation) due to fluid loading (oil and water) is relatively higher when compared to the Torsional and Longitudinal modes. However, at the same operating frequency while using the flexural wave mode the dispersion effect, as well as the change in velocities were observed. The change in frequency was found to be a predominant effect from the F(1,1) reflected signal at each level of waveguide immersion. Therefore, a liquid level sensor can be designed to obtain the exact level measurement based on the amplitude drop, frequency shift and time shifts using flexural wave mode.

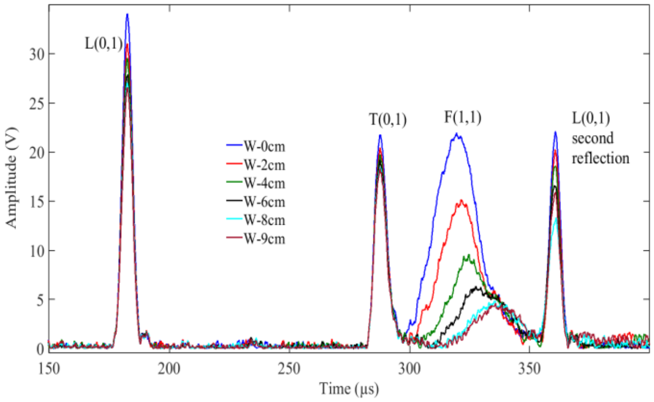

FIGURE 4: THE HILBERT TRANSFORM OF THE REFLECTED L(0,1), T(0,1) AND F(1,1) MODES OBSERVED AT DIFFERENT FLUID LEVELS.

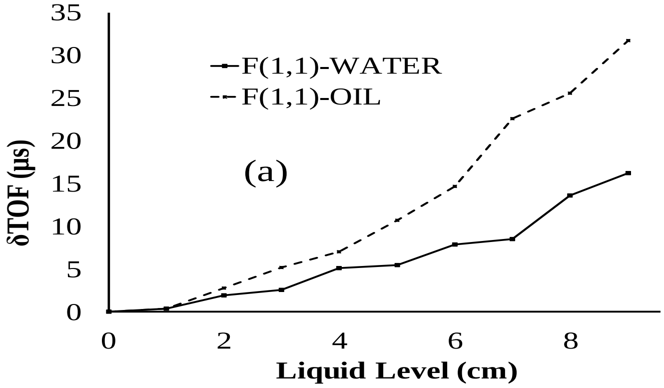

FIGURE 5: CHANGE IN TIME OF FLIGHT (δTOF) OF THE F(1,1) MODES AT DIFFERENT DEPTHS OF FLUID.

4. CONCLUSION

In this work, we reported an novel concept for measuring the level of fluids using an ultrasonic guided wave technique. Here, all three wave modes (L(0,1), T(0,1) and F(1,1)) were simultaneously transmitted/received in thin stainless steel (SS) waveguide using a single shear transducer. The actual experimental condition was replicated in the FEM studies for validating the level measurement experiments. Also, in this study, the dispersive effects were observed for all three wave modes (L(0,1), T(0,1) and F(1,1)) at different fluid levels. The obtained FEM results and experimental results were well in agreement in this level sensor design for level sensing in different fluid medium.

In the same operating frequency when the waveguide was embedded in the fluid at different levels more sensitivity was observed in the flexural wave F(1,1) mode as compared to the other two wave modes (L(0,1) and T(0,1) (i.e significant changes in amplitude drop, frequency shift and time shifts were observed in F(1,1) wave mode. In summary, the proposed waveguide sensor is very robust and can adapt to complex industrial environments for more versatile and redundant measurements of the fluid level in critical enclosures. However, the operating frequency of the flexural mode must be chosen appropriately using the attenuation curve for level measurement experiments. This will be dependent on the material and diameter of the circular waveguide. Other cross-sectional geometries can also be explored in the future studies for understanding the behaviour of F(1,1) modes on different waveguide configuration.

REFERENCES

[1] L. C. Lynnworth, Ultrasonic measurements for process control: theory, techniques, applications. *Academic Press*, (2013).

[2] S.Periyannan, P. Rajagopal and K. Balasubramaniam, *AIP Advances*. 6(6), 065116.2016.

[3] N. Raja, K. Balasubramaniam and S. Periyannan, *IEEE Sensors Journal*. 18, 14, 2018.

[4] R. Kazys, L. Mazeika, R. Sliteris, and R. Raisutis, *Ultrasonics*. 54(4), 2014.

[5] M. G. Silk, and K. F. Bainton, *Ultrasonics*. 17(1), 1979.

[6] V.S.K. Prasad, K. Balasubramaniam, E. Kannan, and K.L. Geisinger, *Journal of Materials Processing Technology*. 207, 313,2008.

[7] T. Vogt, M. Lowe, and P. Cawley, *The Journal of the Acoustical Society of America*. 114(3), 1303,2003.

[8] H. H. Bau, J. O. Kim, L. C. Lynnworth, and T.H. Nguyen, *U.S. Patent*. 4,893,496, 1990.

[9] J. O. Kim, H. H. Bau, Y. Liu, L. C. Lynnworth, S. A. Lynnworth, K. A. Hall and J. A. Korba, *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*. 40(5), 563,1993.

[10] S. Periyannan, and K. Balasubramaniam, *Review of Scientific Instruments*. (11) 114903(1), 2015.

[11] Bo Liu, Dorothy Yunjing Wang, and Anbo Wang. *IEEE Sensors Journal*.16,2317, 2015.

[12] T. J. Knowles, Acoustic flexural order level sensor. *U.S. Patent* 9,285,261. 2016.

[13] B.N. Pavlakovic, M.J.S. Lowe, P. Cawley and D.N. Alleyne, *Rev. Prog.Quant. Non-destr. Eval*. 16, 185 1997.