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Liquid Level Sensing using Lamb waves

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Abstract— **The present study examines the possibility of using an ultrasonic guided wave technique for liquid level sensing. The setup consists of an Aluminium thin beam which is partly immersed in a liquid whose level is to be determined. When a wave guide is immersed in the liquid, guided wave in the waveguide is attenuated due to the leakage of its energy into the surrounding water. The rate of leakage depends on the material properties of the waveguide and that of liquid. With these predictions, it is possible to relate the measured characteristics to the liquid level. Previous research shows that the various modes of Lamb waves are influenced by the surrounding liquid. Therefore, the change in the characteristic of Lamb waves can be used as a function of liquid level. This effect has also been investigated using Finite Element Analysis.**

Keywords- Lamb waves; Acoustic Impedence; Leaky Lamb waves; Energy attenuation; Liquid level Sensing

I. Introduction

Ultrasonic method is one of the effective methods in the field of liquid level measurement. In the process of ultrasonic propagation, attenuation occurs at the interface of the two different media. The extent of attenuation depends on the relative acoustic impedance of the two media. Contact with liquid substantially changes the characteristics of these waves and this can be used as an indicator of liquid presence. This character of the ultrasonic waves is used in the measurement of the liquid level. Theoretical analysis shows that Lamb wave modes, both fundamental and higher order, are sensitive to presence of the liquid.

Level sensors as an integral part of process control gain attention after the Three Mile Accident in 1979. The accident took place due to the malfunctioning of the coolant system, caused by improper coolant level sensing. Thus, level sensing accounts more than just sensing presence or absence of the liquids. The level sensors find their application in petrochemical, chemical, water and waste water, food and beverage, pharmaceutical, and power generation industries. The sensors are also important in monitoring the level of water, slurry, chemicals, petrochemicals, and solids. Fuel level sensing techniques are of great importance in modern engineering scenario. Their application ranges from two wheelers to aircrafts and ordinary fuel storage tanks to aviation fuel tank systems.

In 1917, Horace Lamb, a British applied mathematician, reported the waves discovered in plates [1], and the waves were named after him as Lamb waves. He also established the theoretical rudiments of these waves. The accuracy of liquid-level detection is a key aspect for many applications, such as oil, chemical, meteorological industry, and so on. A variety of principles have been existed, including mechanical, optical, electrical, electromagnetic, and ultrasonic methods. These methods have achieved certain progress on the liquid-level measurement. The mechanical method mainly uses a buoy floating on the liquid to measure the liquid level. The buoy's position can be measured by sliding resistance, radar, or, a single digital camera [2-3]. The mechanical method can be easy to implement, but there is a limit about the kind of liquid and a larger error because of the posture of the buoy. The optical fiber liquid-level measurement is realized by monitoring the valley wavelength shift or the intensity of optical fiber [4-5]. Compared with the other traditional methods, the fiber optic has the advantage of high sensitivity, strong anti-electromagnetic interference capability, corrosion resistance, and compact size [6]. However, current fiber optic level sensors share common disadvantages, including small measurement range and complex mechanical structure. Electromagnetic liquid-level measurement is mainly based on the absorption or reflection by the measured liquid to determine the height of the liquid level [7]–[9]. Different media have different degree of absorption for electromagnetic wave. When using this feature, the liquid level can be measured from different media. Besides, the reflection characteristic of electromagnetic wave can be used to measure the time of-flight, and then calculate the liquid level. However, electromagnetic wave has a larger attenuation, the measuring distance is shorter, and cost is higher. Electrical methods are mainly composed of capacitor methods. The conventional capacitance-type level sensor is based on the linear relationship between the capacitance and the liquid level to measure the liquid level [10-11].

Li et al. [12] proposed an approach to detect the dynamically changed liquid level with the coherent MIMO ultrasonic system. Subhash and Balasubramanium [13] showed the potential of Lamb waves in liquid level sensing using FE simulation. Nayfeh and Nagy [14] studied excess attenuation of leaky Lamb waves due to viscous fluid loading. Sakharov et al. [15] introduced a novel, non-invasive method for measurement of liquid level in closed metal tanks that are under high pressure. It is based on the use of ultrasonic Lamb waves propagating along the tank wall.

The techniques that are recently used are not expected to yield results of high accuracy. The selection of the sensors depends on various constraints like pressure, temperature, density, dielectric constant, composition, vibration, and dynamics of the operating environment. The response rate, non-invasiveness, accuracy, and monitoring and calibration capabilities of the level sensor drastically influence its outcome. Process control and prevention of industrial hazards need much research in this field. There is ample opportunity for growth in ultrasonics, even in an environment where industrial growth may not be significant. The above literature review shows different methods to use the behavior of Lamb Waves for determination of liquid level inside a metal container. Thus, The present work focuses on determining the liquid levels by using experimental and simulative methods.

II. Leaky Lamb Waves

A. Theory

When the plate is immersed in a liquid, the surfaces at the liquid-solid interface are not traction free and the energy of the propagating wave leaks into the surrounding liquid. The propagating wave in this case is called the leaky Lamb wave (LLW). For a plate immersed in a liquid the intensity of energy leaking into the surrounding liquid is not negligible and should not be ignored. Fig. 1 shows the leakage of wave energy in X_2 direction as it passes through the waveguide in X_1 direction, which is immersed in a liquid.

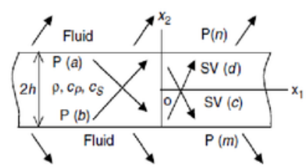

Figure 1. The leaky Lamb wave propagation. [16]

B. Dispersion Curves for Leaky Lamb Waves

Leaky Lamb wave dispersion curves for an Aluminum (Al) plate immersed in the water are given in Fig. 2. Similarities and differences between the Lamb wave dispersion curves (Fig. 3) and leaky Lamb wave dispersion curves (Fig. 2) should be noted here. An extra wave mode of approximately 2 km/s velocity appears when the waveguide is immersed in the water. While in air, the wave exhibits no such mode.

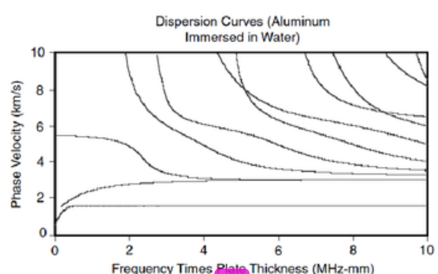

Figure 2. Dispersion curves for 1-mm thick Al plate immersed in water [16].

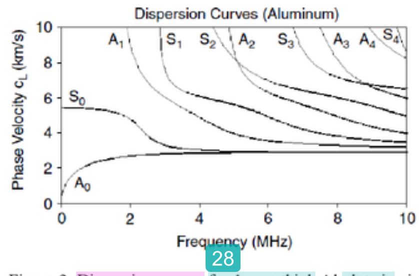

Figure 3. Dispersion curves for 1-mm thick Al plate in air [16].

III. Lamb Waves for Level Sensing

Vogt [17] proposed that a guided wave can be thought of as a superposition of partial bulk waves which are reflected within the wave guide boundaries. When the wave guide is surrounded by vacuum, total reflection occurs. However, if the wave guide is surrounded by any liquid medium, partial waves may also transmit across the interface. Therefore, the energy is carried away resulting in the attenuation of the propagating guided wave. The rate of leakage depends on both the material properties of the waveguide and surrounding medium. As the acoustic impedance of the media is higher, higher will be the attenuation. This takes place due to the increased transmission of partial waves across the interface. Lamb waves can be used to develop a guided wave based liquid level sensor as shown in Fig. 4.

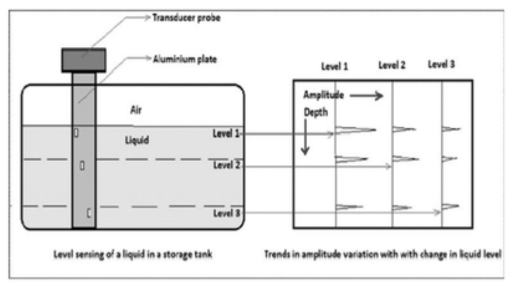

Figure 4. Water level sensing using Lamb waves propagating through an Al plate [13]

A. Selection of Optimum Operating Mode

Dispersion curves, generated in MATLAB©, help to identify and evaluate the possible modes of guided waves and their propagation characteristics in the sample plate. The analysis is done for an Al plate of thickness 1 mm, density 2700 kg/m³, and Young's modulus 70 GPa. In the present case, Lamb waves are generated at the central frequency of 170 kHz using a 8.5 cycle Gaussian windowed tone-burst.

B. Experimental Procedure

The experimental setup shown in Fig. 5 consists of a Single Channel Signal Generator (Tektronix AFG 3015C), Two Channel Digital Oscilloscope (Tektronics TBS 1102B-EDU), SP-5H type Piezoelectric Wafer Transducers (PWT), Computer system for signal processing, and 5052-H32 grade Aluminium plate. For signal acquisition NI LabVIEW© Signal Express software is used. Rectangular PWTs are used for transmitting and sensing Lamb waves. These are bonded onto the plate using a commercially available epoxy based adhesive. The tone burst signal is sent to the actuator to excite Lamb waves. A bucket of approximate capacity of 7 liters is used as a vessel for the experimentation. The function generator and digital oscilloscope are used for excitation and acquisition of the Lamb waves and the plate is simply kept diagonally in the vessel. The experiment is repeated for 4 different water levels and the acquired responses are then processed by using Absolute Deviation. Each Lamb wave response is compared to that of the pristine data and following results are obtained for different water levels.

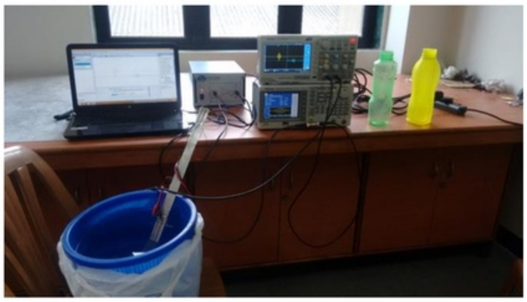

Figure 5. Experimental Setup

C. *Finite Element Simulation*

An Al plate of thickness 1.6 mm and length 1 m is modeled in ANSYS© for the 2D Finite Element Analysis. The material properties are given in Table 1.

TABLE I. PARAMETERS USED IN FINITE ELEMENT SIMULATION

Material Properties	Aluminium Plate	Water
Element type	Plane183	Fluid29
Young's Modulus	70.3 GPa	
Poisson's Ratio	0.33	
Density	2700 kg/m3	1000 kg/m3
Viscosity		8.94E-04 Pa-s
Sonic Velocity		1402 m/s
Boundary Admittance		0.028

The Figs. 6 and 7 show the simulation windows from ANSYS Mechanical APDL for without water and submerged cases respectively.

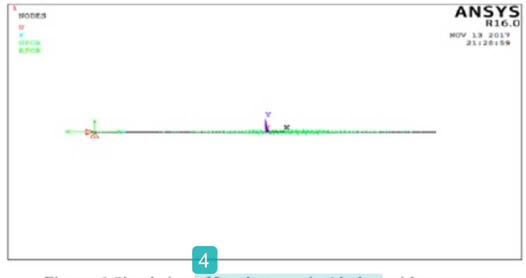

Figure. 6 Simulation of Lamb waves in Al plate without water

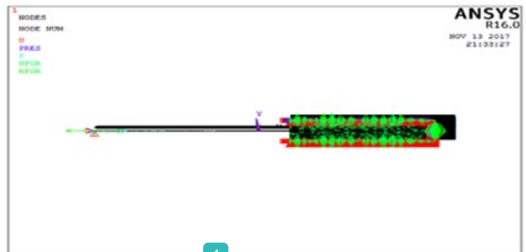

Figure. 7 Simulation of Lamb waves in Al plate with water

D. *Results and Discussion*

Fig. 8 and Fig. 9 show the relation between the water level and Absolute Deviation in the cases of Experimental and Simulation studies respectively.

The figures clearly show that there is a substantial relation between the level of water in the vessel and Lamb wave response. This behavior of Lamb waves can be used to determine the water level in the vessel by calibration of the response based on the values of Absolute Deviation.

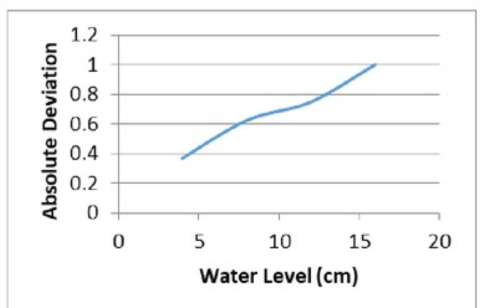

Figure. 8 Graphical representation of normalized Absolute Deviation values at different water levels obtained in experimentations.

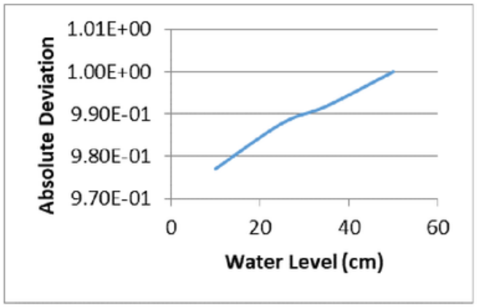

Figure. 9 Graphical representation of normalized Absolute Deviation values at different water levels obtained in simulations.

The Regression Equation $\mathbf{y=0.0007x^3-0.0202x^2+0.2314x-0.2796}$ obtained from experimental results represents the relationship between Absolute Deviation(y) and water level (x).

IV. Concluding Remarks

In present work, a liquid level sensing method using Lamb waves is developed. The behavior of Lamb waves is related with varying water levels. Using Absolute Deviation, the results obtained from the experiments show that as the level of water increases, the similarity in the signals decreases which can be used to calibrate the sensor in terms of Absolute Deviation. Similar results are observed in the Simulation study. Thus, the liquid level sensing using Lamb waves is successfully carried out and a new method for determining the liquid level is successfully proposed and verified through the experiments and Simulation.

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