ULTRASONIC METHOD FOR NONINTRUSIVE LOW-LIQUID-LEVEL SENSING

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INTRODUCTION

The physics and fundamental principles of ultrasonic pulse echo technology are well understood, and pulse echo techniques have been used widely for measurement of materials properties such as modulus, stress, and thickness, and for defect detection and flaw characterization [1,2].

We have applied the pulse echo principle to a new area and developed a nonintrusive method of low-liquid-level sensing for potential application in space systems. The ultrasonic approach to low-liquid sensing provides a viable alternative to conventional approaches, which require the penetration of the container wall and special designs to accommodate the sensor and to access the liquid. Penetration of the container wall may result in high, localized concentrations of stress, which can cause structural weakness, especially in pressurized environments and space applications.

In this paper, we review the theoretical basis for the pulse echo method of nonintrusive low-liquid-level sensing, and present the results of an analysis and several laboratory experiments we conducted to study the sensitivity and functional relationship between the signal amplitude and the liquid level across the face of the transducer. The purpose of this study was to verify the operating principle of the system experimentally. The results of the experiments have verified the applicability of this ultrasonic nonintrusive method of low-liquid-level sensing.

BACKGROUND AND ANALYSIS

The basic structure of the low-liquid-level sensing system is shown in Fig. 1. In this case, a pulse is reflected through two layers [3], the epoxy adhesive that bonds the sensor to the container wall and the container wall itself. The acoustic reflection coefficient for the

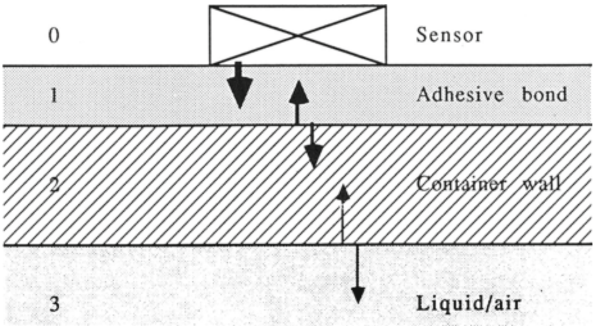


Fig. 1. Basic structure of the ultrasonic low-liquid sensing system.

container wall varies depending on whether the liquid backing (i.e., fuel) is present or absent (i.e., air), and thus is used as an indicator of the level of the liquid backing.

The functional relationship of time (T_{mn}) and acoustic amplitude response (A_{mn}), for such a two-layered structure can be written as

$$T_{mn} = m\, t_1 + n\, t_2, \qquad (1)$$

where t = 2 d/v (d is the thickness and v is the velocity of the media), and

$$A_{mn} = A_0\, T_{10}\, R_{10}^{\,m-1}\, R_{12}^{\,m+n}\, R_{23}^{\,n}\, \exp(-2m\alpha_1 d_1 - 2n\alpha_2 d_2) \;*$$

$$\sum_{k=1}^{\min(m,n)} (-1)^{n-k} \binom{m}{k} \binom{n-1}{k-1} \left(\frac{1}{R_{12}^{2}} - 1 \right)^{k} \qquad (2)$$

where $\binom{m}{n} = \frac{m!}{n!\,(m-n)!}$, m and n are numbers of reverberations in medium 1 and 2, T_{10} is the transmission coefficient to the transducer A_0 is the incident amplitude, and $R_{ij} = (Z_j - Z_i)/(Z_i + Z_j)$ is the reflection coefficient of medium i to medium j [$Z = \rho V$ (the product of acoustic velocity and density) is the acoustic impedance]. For our applications, the only variable is the amplitude of the acoustic signal from the container wall to the fuel or air interface, which is the ratio of the nth echo amplitude for the container wall with a liquid backing (i.e., fuel) and without (i.e., air). This can be expressed as

$$(A_{mn}/A'_{mn}) = (R_{23}/R'_{23})^{n} \qquad (3)$$

where R_{23} is the reflection coefficient for the container wall backed by a liquid, and R'_{23} is the reflection coefficient for the container wall backed by air. As Eq. (3) indicates, the most sensitive echo to use in such applications is to select the highest detectable echo with an appropriate signal-to-noise ratio.

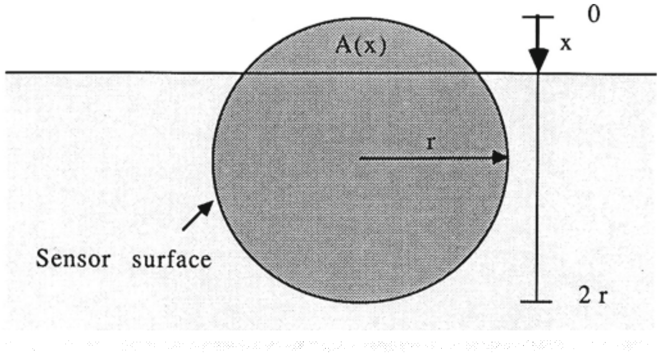


Fig. 2. The uncovered surface area [A(x)] of the transducer as liquid level (x) decreases.

We also investigated the sensitivity of the system. As Fig. 2 shows, the sensor face is uncovered as the liquid level drops. Thus, the amplitude of the signal from Eq. (2) is a function of the effective reflection coefficient, R_{eff}. R_{eff} is related to R_{23}, R'_{23}, and the liquid level, x, via the percentage of area uncovered, A(x). For the first-order approximation, R_{eff} may be written as a simple linear combination of R_{23} and R'_{23} as

$$R_{eff} = R'_{23}\, A(x)+R_{23}\, (1-A(x)). \tag{4}$$

where $A(x) = (\beta - \sin\beta \cos\beta)/\pi$ and $\beta = \cos^{-1}(1 - x/r)$ for a circular sensor.

CONFIGURATION AND EXPERIMENTS

Configuration

Figure 3 is a block diagram of the ultrasonic nonintrusive low-liquid-level sensing system.

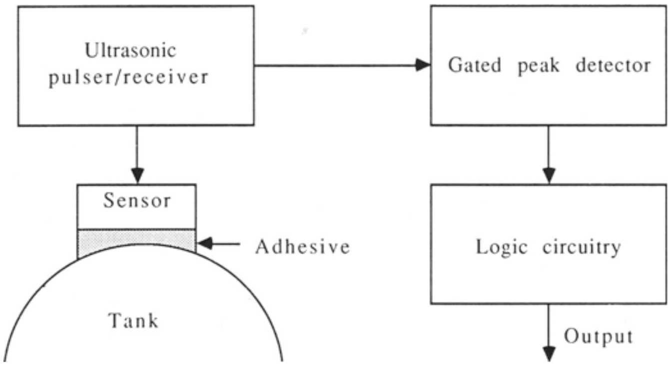


Fig. 3. Block diagram of the ultrasonic nonintrusive low-liquid-level sensing system.

The system consists of three major components: a sensor, an adhesive bond, and the electronics. The sensor is a specially designed ultrasonic transducer that can withstand the environmental effects likely to be encountered in space applications, such as g-load, vibration, and thermal cycles. The adhesive also must meet the adhesion requirements for space applications and have acceptable acoustic properties. We tested adhesives experimentally and selected Versilok 202 to bond the sensor to the tank. Finally, the electronics in the sensing system includes a customized ultrasonic pulser/receiver, accept/reject logic circuitry, and the desired signal output.

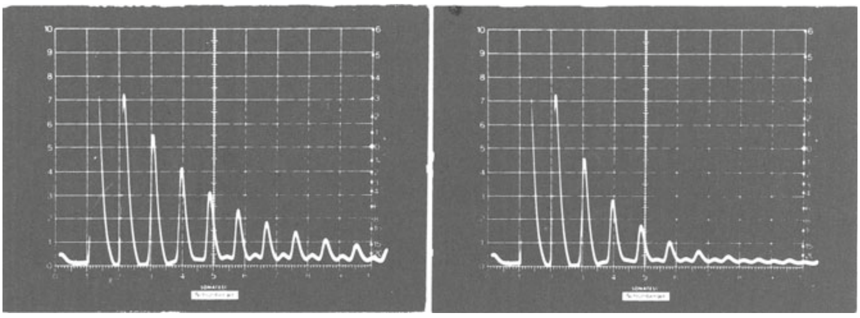
Experimental Procedures and Results

To demonstrate the principle of operation, we used common commercial instruments (1/4-in.-diameter 5-MHz transducers from various vendors and a Sonatest UFDS unit as the pulser/receiver), and two aluminum plates (0.09- and 0.197-in. thick, respectively), with and without water backing.

The performance of the system strongly depends on the combined performances of the ultrasonic pulser/receiver and the transducer. In general, all the transducers we used displayed similar signal responses but with different amplitudes. Typical ultrasonic responses with and without the liquid backing are shown in Fig. 4. By selecting the most suitable echo (the highest detectable echo with an appropriate signal-to-noise ratio), we can use the ultrasonic signal as a low-liquid monitor. We selected the seventh echo.

The sensitivity of such a system is related to the sensitivity of the gated peak detector. To determine the sensitivity of this system, we monitored the amplitudes of four echos -- the fourth, fifth, sixth, and seventh -- as a function of liquid level.

The normalized ultrasonic amplitude vs the normalized liquid level for these echos is shown in Fig. 5. The general shapes of these curves agree well with those determined using Eq. (4). The sensitivity of this experimental setup is estimated to be 0.1 in.



(a) Ultrasonic signal response (with air backing)

(b) Ultrasonic signal response (with liquid backing)

Fig. 4. Typical oscilloscope tracings showing the response of the transducer while covered and uncovered.

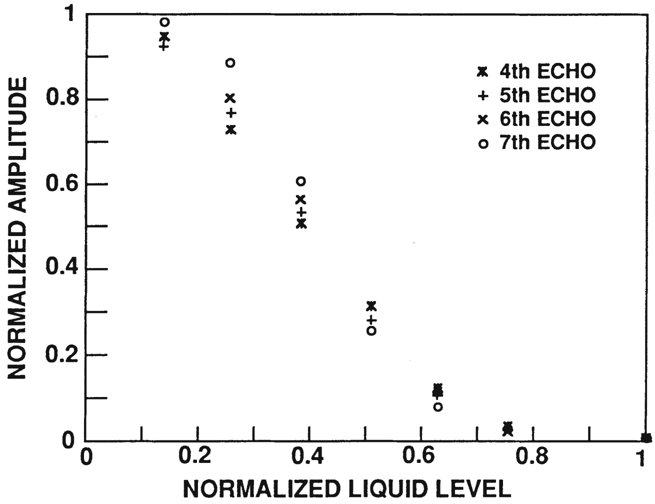


Fig. 5. Normalized ultrasonic amplitude vs normalized liquid level for echos #4-7.

Finally, we performed independent experiments to determine the ultrasonic signal response of various adhesives. The results for two of these adhesives, Versilok 202 and 204, are provided in Fig. 6.

As this shows, Versilok 204 has better acoustic properties than Versilok 202. However, Versilok 204 requires 24 h to be fully cured, whereas Versilok 202 is cured after only 3 min. Since the signal amplitude can easily be adjusted to meet the design requirements using the electronic gain circuitry, Versilok 202 was selected for its ease of bonding.

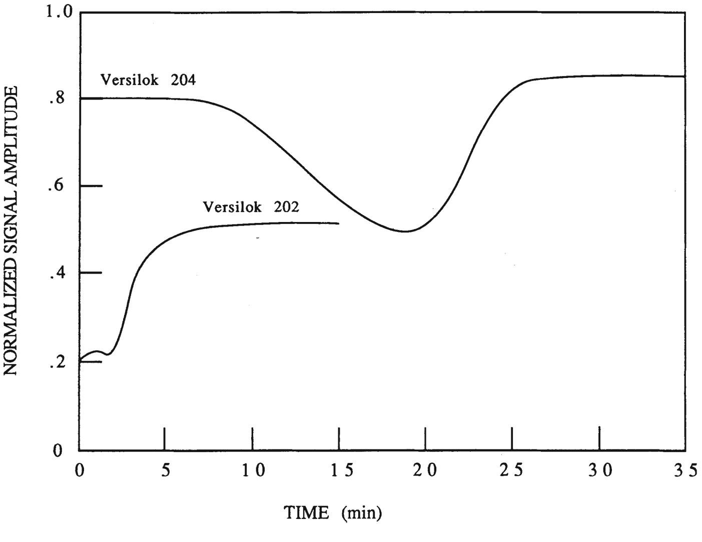


Fig. 6. Ultrasonic amplitude response as a function of curing time for two adhesives, Versilok 202 and 204.

DISCUSSION AND CONCLUSION

The results from these laboratory experiments have clearly verified the operating principle for low-liquid-level sensing. The next step is to establish procedures regarding: 1) sensor variation, 2) adhesive cure monitoring, 3) signal normalization, 4) environmental effects, and 5) functionality checks. Each issue is discussed separately below.

Manufacturing sensors is a very complicated process and difficult to control, and thus the performance of the sensors may vary drastically. A test procedure, such as measuring the reflected amplitude from an aluminum plate through a fixed-distance water path, should be established to standardize the performance of the sensors.

A procedure is needed to determine the proper acoustic pattern of an acceptable bond during the curing process. The sensor is wasted if the bond is rejected after the adhesive is cured because the sensor is bonded and cannot be removed. Once the proper pattern is established, the bonding process can be aborted during curing if the signal response does not meet the criteria, and the sensor can be salvaged.

The performance of the entire low-liquid-level system depends on the combined performances of its components, the sensor, the adhesive bond, and the electronic circuitry. A method of gain adjustment should be incorporated into the system's electronic circuitry to compensate for variations in the signal caused by variations in the sensor and the adhesive bond.

Temperature, humidity, and adherend surface preparation dictate the adhesive curing time and influence the level of acoustic response attained. Acceptable environmental conditions for bonding the sensor must be defined to ensure proper installation and thus performance comparability.

Finally, the system must be periodically monitored during installation and while in service to ensure that it is functioning properly. An array of LED indicators should be included on the electronic panel for monitoring signal output.

In conclusion, we have reviewed and verified the theoretical principles applied to an ultrasonic low-liquid-level sensing system. The results from the laboratory experiments and a computer analysis have demonstrated the validity of the approach and the applicability of the ultrasonic principle for low-liquid-level sensing. In future work, we shall investigate the practical considerations listed above to optimize field installation and in-service monitoring.

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