AN ULTRASONIC RESONANCE METHOD TO DETERMINE THE ACOUSTIC VELOCITY OF THIN ADHESIVE LAYERS

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INTRODUCTION

The development of this ultrasonic method for determining the modulus of thin adhesive layers was motivated by the recent development of a nonintrusive ultrasonic Liquid Level Sensor (LLS) which meets military specifications for space launch [1,2]. The sensor is designed to signal when the surface of the fuel in a liquid propellant tank has receded to the level of the sensor during flight. As depicted in Fig. 1, the sensor is bonded to the outer tank wall with Versilok 202 (V202) adhesive [3]. To detect the fuel level, the sensor is stimulated to propagate an ultrasonic pulse into the wall of the tank and then used to monitor the height of echoes which return from the inner wall. More details on the basic operation of the sensor are given in references 1 and 2.

![Figure 1. Schematic representation of the LLS. The aluminum sensor faceplate is bonded to the aluminum tank wall with Versilok 202 adhesive. The standoffs provide a fixed separation.](image)
Though the sensors were designed to be interchangeable, it was noted early in the program that the amplitude of the returning echoes varied significantly from sensor to sensor upon installation in preparation for launch. One possible explanation for this discrepancy is concerned with the acoustic properties of the V202. The front face of the sensor is a flat aluminum plate. As denoted in Fig. 1, a torlon ring with three standoffs is embedded in this plate. These standoffs serve to control the thickness of the adhesive layer between the faceplate and the tank wall as this parameter can strongly influence the amplitude of the received signal. The nominal operating frequency of the sensors is 5 MHz. As will be seen from calculations which follow, for maximum acoustic power transmission, these standoffs should be machined so that the thickness of the glue layer is a multiple of $\lambda/2$, where $\lambda$ is the wavelength of the ultrasound in the glue. The wavelength of the ultrasound in the glue can be obtained from the relation $\lambda = v/f$ where $v$ is the acoustic velocity and $f$ is the ultrasonic frequency. It can be seen from this relationship that even if the adhesive layer thickness is consistent from sensor to sensor as per design, that variations in the acoustic properties of the glue could lead to overall signal degradation. In discussions with those contracted to design and build the sensors, it was ascertained that the degree of variation in the acoustic velocity of the V202 had not been studied. In addition, it was determined that a technique for measuring the acoustic velocity of the V202 as a thin layer had not been developed. The value used for the sensor design was that of a similar glue (Versilok 204) whose acoustic velocity in a thin layer was more easily determined.

In light of the discussion above, the objectives of this study were threefold. First, a technique was developed to measure the acoustic velocity $v$, of a thin layer (less than $\lambda$ at 5 MHz) of cured V202. Second, this technique was used to bracket the variation in $v$ between different cures under similar conditions and with respect to changes in temperature and humidity during cure. Finally, this data was used to estimate the effect such variation would have on the signal response of the LLS.

THEORY

Consider first the semi-infinite medium (labeled Medium 1), with acoustic impedance $Z_1$, as depicted in Fig. 2. If a thin layer of a second medium, Medium 2, with acoustic impedance $Z_2$, is placed in contact with the left side of Medium 1, the input impedance of the composite system (Medium 1 + Medium 2) is given by the complex relation:

$$Z_{21} = \frac{Z_2Z_1\cos(x_2\beta_2) + j Z_2^2\sin(x_2\beta_2)}{Z_2\cos(x_2\beta_2) + j Z_1\sin(x_2\beta_2)}$$  \hspace{1cm} (1)$$

where $x_2$ is the thickness of Medium 2, $\beta_2 = 2\pi/\lambda$ is the propagation constant of Medium 2 and $j$ is the imaginary index [4]. It might be noted that in the derivation of Eqn. 1, a steady state condition (continuous plane wave stimulation of the system) was assumed.

Next, consider what happens when a third (semi-infinite) medium, Medium 3, is placed in contact with the left side of Medium 2 as is also depicted in Fig. 2. If this medium has the same acoustic impedance as that of Medium 1, then the stress wave reflection coefficient $R$, is given by the relation:

$$R = \frac{Z_2Z_1\cos(x_2\beta_2) + j Z_2^2\sin(x_2\beta_2) - Z_1(Z_2\cos(x_2\beta_2) + j Z_1\sin(x_2\beta_2))}{Z_2Z_1\cos(x_2\beta_2) + j Z_2^2\sin(x_2\beta_2) + Z_1(Z_2\cos(x_2\beta_2) + j Z_1\sin(x_2\beta_2))}.$$  \hspace{1cm} (2)$$

The coefficient of acoustic power transfer $P_T$, across Medium 2 can now be calculated.
Figure 2. A thin medium of acoustic impedance $Z_2$, sandwiched between two semi-infinite media. Medium 3 sees the composite system formed by Medium 1 and Medium 2 as having an input acoustic impedance of $Z_{21}$.

$$P_T = 1 - |R|^2 = 1 - \frac{(Z_2^2 - Z_1^2)^2 \sin^2(x_2 \beta_2)}{(Z_1^2 + Z_2^2)^2 \sin^2(x_2 \beta_2) + 4Z_2^2Z_1^2 \cos^2(x_2 \beta_2)}.$$  \hspace{1cm} (3)

which can be further reduced to:

$$P_T = \frac{4Z_2^2Z_1^2}{(Z_1^2 + Z_2^2)^2 \sin^2(x_2 \beta_2) + 4Z_2^2Z_1^2 \cos^2(x_2 \beta_2)}.$$  \hspace{1cm} (4)

The transformation of variables $x_2 \beta_2 \rightarrow 2\pi x$ can be applied to Eqn. 4, so that as $x$ varies from 0 to 1, the thickness of Medium 2 varies from 0 to $\lambda$. In Fig. 3, Eqn. 4 is plotted for the case where Mediums 1 & 3 are glass ($Z_1 = 18.9$ Rayls) and Medium 2 is V202 ($Z_2 = 2.6$ Rayls). These values have been chosen for reasons which will become apparent later in the text. It can be seen that the condition of maximum power transmission occurs when the thickness of Medium 2 is a multiple of $\lambda/2$. It should be noted that Medium 2 was assumed to be lossless in the derivation of Eqn. 4. In actuality, one would expect the local maximum to be highest for zero thickness and to be slightly less for each successive $\lambda/2$ multiple after that. It should also be noted that local minima occur for thicknesses equal to $(2n+1)\lambda/4$ where $n$ is an integer. The LLS can be represented by an Al/V202/Al sandwich. For purposes of comparison, in Fig. 3, Eqn. 4 is replotted assuming Mediums 1 and 3 to be aluminum ($Z_1 = 17$ Rayls).

If one assumes that $x_2 = \lambda_R/2$ where $\lambda_R = v/f_R$, Eqn. 4 reduces to:

$$P_T = \frac{4Z_2^2Z_1^2}{(Z_1^2 + Z_2^2)^2 \sin^2(\pi f)_{f_R} + 4Z_2^2Z_1^2 \cos^2(\pi f)_{f_R}}.$$  \hspace{1cm} (5)

and it becomes clear that the system depicted in Fig. 2 can also be examined as a function of frequency. Eqn. 5 exhibits the same functional form as Eqn. 4 with local maxima occurring when $f$ is an integral multiple of $f_R$. 

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Figure 3. Acoustic power transmission coefficient (Eqn. 4) as a function of $x$ assuming Mediums 1 and 3 to be glass (thick) and aluminum (thin) and Medium 2 to be V202. The variable $x$ is the thickness of Medium 2 in units of $\lambda$ (at 5 MHz in Medium 2).

TECHNIQUE

The frequency dependence of the power transfer coefficient expressed in Eqn. 5 can be used to determine the acoustic velocity of a thin layer of material (such as an adhesive). The conditions which led to the derivation of this equation are approximated by the apparatus depicted in Fig. 4. A thin layer of the material is sandwiched between two glass plates as shown. The spacing between the plates and hence, the material thickness, is determined by wire spacers. The thickness (0.0127 - 0.0254 cm) of these spacers is chosen to promote a resonant frequency near 5 MHz (nominal operating frequency of the LLS). The glass plates are purposely chosen to be significantly thicker than that of the spacing between them. The glass/material/glass sandwich thus formed is immersed in a water tank (if necessary the edges of the glass are sealed) between a pair of 5 MHz, plane wave, through transmission transducers.

To perform the measurement, one transducer is stimulated to propagate a toneburst (single frequency) pulse. The pulse duration is chosen to be $\sim$ 1.5 $\mu$s which is assumed long enough to allow the reverberations within the thin material layer to approximate a steady state, yet short enough so that reverberations in the glass do not overlap each other. This pulse traverses the glass/material/glass sandwich and is then received by the opposite transducer. The amplitude of the first part of the received pulse (that which is unaffected by reverberations within the glass) is monitored as a function of frequency (between 2 and 8 MHz). The data thus obtained is then corrected for the frequency response of the transducers, normalized and plotted (amplitude vs. frequency). The peak in this plot occurs at $f_R$ (see Eqn. 5) whose value can be used to determine the acoustic velocity, $v$, of the sandwiched material ($v = 2xf_R$, where $x$ is the thickness of the material layer).

VALIDATION OF TECHNIQUE

The described technique was tested for a known standard, namely, water. Three glass/water/glass specimens, denoted as S1, S2, and S3, with wire spacers of 0.00978, 0.0123 and 0.0159 cm, respectively, were tested. The raw (normalized) data for a water layer thickness of $x_w = 0.00978$ cm is presented in Fig. 5 (circles). The normalized transducer response, obtained by using the same apparatus (Fig. 4) with no specimen present (i.e., a clear water path) is also plotted (boxes). The solid line curve in this figure was produced by dividing the transducer response curve into that of the raw data and
normalizing the result. Comparison of the peak position of this raw data to that of the solid curve reveals the importance of the transducer response correction.

The (corrected) experimental and theoretical curves for S1, S2, and S3 are depicted in Fig. 6. The theoretical curves were generated using Eqn. 5 and taking note that the amplitude response is proportional to the square root of $P_T$. The experiment is well approximated by theory. It might be noted that as predicted, peaks occur according to the relation; $f_R = v_w/2x_w$, where $v_w$ is the acoustic velocity of water, and that the peak width grows as $x_w$ decreases. The experimental peaks are, however, broader than Eqn. 5 predicts. Several effects would contribute to this broadening. The ultrasonic pulses, by virtue of their finite duration, are not strictly monotonic. In addition, the transducers used do not produce perfect plane waves. Finally, one would also expect misalignments of the components in the experimental apparatus to broaden the peaks. The value obtained for each specimen for the acoustic velocity of water is listed in Table 1. As indicated, the values cluster within 1.0% of their average value of 1454 m/s. This variation is consistent with the accuracy to which $f_R$ was measured. It might also be noted that the experimental values fall within 2.8 % of 1480 m/s, the text value for water. This (slight) discrepancy has since been traced to a consistent mismeasurement (too much pressure was applied) of the copper wire thickness.

Table 1. Results for measurement technique applied to water.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$x_w$(mm)</th>
<th>$f_R$ (MHz)</th>
<th>$v_w$ (m/s)</th>
<th>$v_w$ -1480 (%)</th>
<th>$v_w$ -1454 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.0978</td>
<td>7.36</td>
<td>1440</td>
<td>-2.70</td>
<td>-0.96</td>
</tr>
<tr>
<td>S2</td>
<td>0.123</td>
<td>5.93</td>
<td>1459</td>
<td>-1.42</td>
<td>0.34</td>
</tr>
<tr>
<td>S3</td>
<td>0.159</td>
<td>4.6</td>
<td>1463</td>
<td>-1.15</td>
<td>0.62</td>
</tr>
</tbody>
</table>
RESULTS FOR V202 AND IMPLICATIONS FOR THE LLS

The aforementioned technique was applied toward the measurement of the acoustic velocity of Versilok 202 adhesive, $v_{v202}$. For a standard (room temperature) cure, an average value of $v_{v202} = 2464$ m/s was measured with an assumed precision of ± 9 m/s. The variation in $v_{v202}$ for cures under different environmental conditions was also investigated. The results indicate that temperature variations between 4 C and 40 C may serve to decrease $v_{v202}$ by as much as 12%. It should be noted that these are severe temperature extremes. One sample was prepared in a humid (saturated) environment. The $v_{v202}$ value measured for this specimen was slightly (3%) lower than that reported above.

Figure 5. Sample data for S1. The transducer response (boxes) is divided into the raw data (circles) to generate the solid curve from which $f_R$ is determined.

Figure 6. Comparison of experimental and theoretical curves for S1, S2, and S3. For simplicity, the water velocity determined by this experiment was also used to generate the theoretical curves. Using the text value of 1483 m/s would have shifted the peaks of the theoretical curves slightly (<3%) with respect to the experimental data.
In addition, a sample prepared with extra accelerator exhibited a value 4% below the reported value.

Given the value $v_{202} = 2464 \pm 9$ m/s, Eqn. 4 indicates that maximum signal transmission at 5 MHz should occur for an adhesive thickness of $x_{202} = \lambda/2 = 0.025$ cm. Were the sensor designed with standoffs of thickness $x_{202} = 0.025$ cm, then a 12% reduction in $v_{202}$ would result in an 89% reduction of signal amplitude (or a 98.8% reduction in signal power). This figure is based on Eqn. 4, taking note of the fact that the sensor functions in pulse-echo mode so that the through-transmission coefficient $P_T$, should be squared. As noted, Eqn. 4 is an approximation. The signal reduction would actually be mitigated by a number of factors (in much the same way that the experimental peaks of Fig. 6 are broadened). The sensor is stimulated by a spike pulse, which though centered at ~ 5 MHz, is actually composed of a distribution of frequencies. In addition, the sensor is mounted on a slightly curved surface so that the V202 thickness varies across the face of the sensor.

It should be noted that the original design for the LLS involved a logic scheme that was critically dependent on the signal amplitude via a preset threshold. The detection scheme has since been modified to eliminate the need for this threshold. Consequently, the LLS will be less sensitive to variations in signal power transfer (caused by variations in the glue velocity).

SUMMARY

A technique for measuring the acoustic velocity of thin specimens was developed. This technique was tested for a known material (water) and found to produce a value within 3% of the expected value. This technique was then applied toward the measurement of the acoustic velocity of Versilok 202 adhesive. For a standard room temperature cure, the value, $v_{202} = 2464$ m/s, is reported. This value was found to vary by as much as 12% for cure temperatures between 4 and 40 C. Implications of such a variation for LLS performance were also discussed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the advice and assistance of J. N. Schurr, J. R. Lhota and G. F. Hawkins.

REFERENCES