A REFLECTION ULTRASONIC INTERFERENCE METHOD FOR MEASUREMENT
OF THE ACOUSTIC VELOCITY OF THIN LAYERS

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INTRODUCTION

Ultrasonic waves can be used to measure the velocities and other properties of a material layer by determining the difference in the time-of-flight of the successive echoes from the backwall of the layer. The top and bottom surfaces must be sufficiently far apart for the successive echoes to be distinct. This method can be used to measure the velocity of a protective epoxy layer on a pipeline wall to determine the deviation of an ultrasonic wave scattered from a defect. It has been used to determine the strength of adhesive bonds [1].

When the top and bottom surfaces of the layer are not sufficiently far apart to produce distinct echoes, the echo pattern is too confused to be interpreted. The nominal minimum resolvable spacing is one-half the pulse length in the medium, where the pulse length is the sonic velocity times the pulse duration.

It has been demonstrated by Lees [2] that if the spacing between the two surfaces was far less than the pulse length, useful information could be extracted from the wave shape of a pulse echo. The echo wave shape was calculated from the one-dimensional wave equation with appropriate boundary conditions for a three-layer system. The longitudinal acoustic velocity and the associated specific acoustic impedance had to be known for each layer. A curve was produced by plotting the peak ratios in the echo for various film thicknesses. An unknown film thickness could then be estimated by measuring the peak ratios in the echo. However, the same pulse used for the calibration curve had to be transmitted into the film. Furthermore, different calibration curves needed to be devised for different materials.

A method that eliminated all of these problems was proposed by Johnson and Sherman [3]. Two transducers were used. The transmission pressure signal amplitude experienced a local maximum at a certain frequency which was a function of the velocity and thickness of the material layer. If the frequency was measured, either the velocity, or the thickness of the layer could be determined. However, the transducers had to be well aligned and the measurement had to be performed in a water tank.
A contact method that uses a single broadband transducer will be described here. The reflected pressure amplitude experiences various local minima at different frequencies which are a function of the velocity of the thin layer.

It should be noted that all these three methods employ the same basic principle, that the various reflected waves at the thin layer interfere with the incident wave and combine into a steady-state. Although all the methods allow the thickness of the layer to be measured if its velocity is known, only the last two allow the velocity of the layer to be measured if the thickness is known.

THEORY

It is assumed that a layer of uniform thickness \( L \) lies between two dissimilar media (Figure 1) and that a plane wave is normally incident from Medium 1 on the boundary between Media 1 and 2. Let the characteristic impedances of the media be \( r_1, r_2 \) and \( r_3 \), respectively. When an incident wave in Medium 1 first arrives at the boundary between 1 and 2, some of the energy is reflected and some is transmitted into the second Medium. The portion of the wave transmitted will proceed through Medium 2 to intersect with the boundary between Media 2 and 3, where again some of the energy is reflected and some transmitted. The reflected wave proceeds back to the boundary between Media 1 and 2, and the whole process is repeated. If the incident wave train is long compared with \( 2L \), the various transmitted and reflected waves combine into a steady-state. The pressure reflection coefficient from Medium 1 to Medium 3 is given by [4]:

\[
R_{13} = \frac{n_1 c + jn_2 s}{d_1 c + jd_2 s}
\]

where

\[
\begin{align*}
    n_1 &= r_2 r_3 - r_1 r_2 \\
    n_2 &= r_2^2 - r_1 r_3 \\
    d_1 &= r_2 r_3 + r_1 r_2 \\
    d_2 &= r_2^2 + r_1 r_3 \\
    c &= \cos(\theta) \\
    s &= \sin(\theta) \\
    \theta &= \frac{2\pi f}{v_2} L
\end{align*}
\]

where \( f \) is the frequency of the wave and \( v_2 \) is the velocity of the wave in Medium 2. The phase of \( R_{13} \), \( \Phi_{R13} \) is then given by

\[
\Phi_{R13} = \tan^{-1}\left( \frac{n_2 d_1 c s - n_1 d_2 c s}{n_1 d_1 c^2 + n_2 d_2 s^2} \right)
\]

![Fig. 1. A layer of uniform thickness L lies between two dissimilar Media, 2 and 3.](image)
Fig. 2. The reflection coefficient amplitude $|R_{13}|$ plotted versus frequency.

Figures 2 and 3 exhibit $|R_{13}|$ and $\Phi_{R_{13}}$ with respect to frequency. Medium 1 is fused silica, Medium 2 is a polymer layer of thickness 69 $\mu$m, and Medium 3 is aluminum. The characteristics of the media are given in Table 1.

By differentiating $|R_{13}|^2$ with respect to $\theta$, it can be shown that $|R_{13}|$ experiences local maxima when $c = 0$, i.e.,

$$f_{\text{max}} = \frac{(2n + 1) v^2}{4L} \quad n = 0, 1, 2, \ldots$$  \hspace{1cm} (10)

At the local maxima, $\Phi_{R_{13}}$ equals $\pm \pi$ radians.

It can also be shown that $|R_{13}|$ experiences absolute minima when $s = 0$, i.e.

$$f_{\text{min}} = \frac{n v^2}{2L} \quad n = 0, 1, 2, \ldots$$  \hspace{1cm} (11)

At the absolute minima, $\Phi_{R_{13}}$ equals 0 radians.

Fig. 3. The phase of the reflection coefficient, $\Phi_{R_{13}}$ plotted versus frequency.
Table 1. Properties of the materials used in the calculations

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Density ($g/cm^3$)</th>
<th>Longitudinal Velocity (mm/μs)</th>
<th>Acoustic Impedance ($g/cm^2s \times 10^5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused silica</td>
<td>2.2046</td>
<td>5.8768</td>
<td>12.96</td>
</tr>
<tr>
<td>Polymer</td>
<td>0.958</td>
<td>2.08</td>
<td>1.993</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.71</td>
<td>6.43</td>
<td>17.425</td>
</tr>
</tbody>
</table>

EXPERIMENT

The frequency dependence of the pressure reflection coefficient can be used to determine the acoustic velocity of a thin layer of material if the thickness of the material is known. As the minima are quite cusp-like while the maxima are quite flat, it will be more accurate experimentally to locate the frequencies where minima occur.

A Panametrics 20 MHz, 6.35 mm diameter transducer bonded to a 12.7 mm long fused silica delay rod was used. The round trip travel time in the delay rod was 4.25 μs.

A MATEC MBS 8000 ultrasonic testing system, with a GA-825 RF gated amplifier (2-100 MHz bandwidth) was employed to transmit a toneburst (single frequency) pulse of duration chosen to be 3.0 μs. The pulse was excited from the transducer into the buffer rod. When the buffer rod was not coupled to any specimen, the front surface of the buffer rod reflected back a signal $A'$. A window of 5.0 μs duration, containing the signal $A'$, was averaged 64 times, and the digitized data from 1024 sampling points were stored. The frequency was changed from 8 to 32 MHz in steps of 2 MHz and all the signals $A'$ were recorded.

A thin polymer layer of thickness 106 μm or 69 μm was sandwiched between the fused silica rod and an aluminium 6061 T6 rectangular block (Fig. 4). Gorptech gel was used as a couplant. An ultrasonic pulse duration of 3.0 μs was assumed to be long enough to allow the reverberation within the thin polymer layer to approximate a steady-state, yet short enough so that reverberations in the buffer rod and in the aluminum block would not overlap each other. The reflected signal from the front surface of the buffer rod interfering with reverberation from the polymer layer was stored as Signal $A$. Examples of Signals $A'$ and $A$ are shown in Fig. 5. The frequency was again swept from 8 to 32 MHz in steps of 2 MHz and all the $A$ signals were recorded. The reflection coefficient $R$ was then calculated as [5]

$$R = \frac{A}{A'}$$

(12)

Fig. 4. The experimental set-up.
It was noted that the frequency of the maximum amplitude of the frequency spectrum of Signal A' was lower than that of the toneburst frequency transmitted into the transducer. This was caused by the frequency response and attenuation of the fused silica buffer rod.

A Fast Fourier transform of Signal A' was performed. The frequency channel whose amplitude was an absolute maximum, and its two adjacent channels were employed to fit a parabola whose local maximum then yielded the peak frequency of Signal A'. A Brute Force transform was then used to find the amplitudes of this peak frequency for Signals A' and A. This procedure increased the accuracy of the experimental data. The amplitude and phase of the reflection coefficient of this peak frequency were then calculated from Eq (12). Data of reflection coefficient versus peak frequency showed local minima which were cusp-like. A parabolic fit at each local minimum would yield a more accurate minimum of the parabola. Even though the reflection coefficient was cusp-like at the local minimum, it was estimated that a parabolic fit would yield a reasonably accurate answer.

The thickness of the polymer layer was measured by a micrometer. The velocity, \( v_2 \), of the layer could then be calculated from Eq (11).

RESULTS

A polymer layer of thickness 106 \( \mu \text{m} \) was sandwiched between the fused silica buffer rod and a rectangular aluminum block. A spike pulse was sent to the transducer using a Panametrics pulser/receiver model 5601A. The first and second backwall echoes of the polymer layer were sufficiently far apart to be distinct. Using the echo overlap method [6], the velocity of the polymer was found to be 2.08 mm/\( \mu \text{s} \). Equation (11) was used to calculate the frequencies where minima of the reflection coefficient occurred. A toneburst sine wave of pulse duration 3.0 \( \mu \text{s} \) was then transmitted to the transducer. As noted earlier, because of the impulse response of the buffer rod, the frequency corresponding to the maximum amplitude of the frequency spectrum of Signal A' was lower than the input frequency. These values of the peak frequencies are listed in Table 2. The reflection coefficients corresponding to the peak frequencies are plotted in Fig. 6. The minima were deduced and compared with the results of the theoretical calculation in Table 3.

The 9.81 MHz minimum was not observed experimentally. The experimental values of the two higher frequency minima agree with the results of the theoretical calculation to within 2\%. The
Table 2. Input and altered frequencies from buffer rod

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Input</th>
<th>Altered</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7.96</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9.90</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>11.81</td>
<td></td>
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<tr>
<td>14</td>
<td>13.81</td>
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<tr>
<td>16</td>
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</tr>
<tr>
<td>18</td>
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</tr>
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<td>20</td>
<td>19.47</td>
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<tr>
<td>22</td>
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<tr>
<td>24</td>
<td>23.30</td>
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</tr>
<tr>
<td>26</td>
<td>25.28</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>27.18</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>29.01</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>30.95</td>
<td></td>
</tr>
</tbody>
</table>

Theoretical phase of the reflection coefficient is plotted in Fig. 7, together with the experimental phase. While the two agreed reasonably at frequencies away from the minima, the experimental phase at the minima differed drastically from the theoretical phase which was calculated to be zero. This discrepancy may be caused by the couplant thicknesses in the experiment which were not taken into account in the theoretical model.

A polymer layer of thickness 69 μm was then used in the experiment. A spike pulse was sent to the transducer. The first and second backwall echoes of the polymer layer were overlapping with each other. An approximate value of the velocity could only be found by the echo overlap method. It was estimated to be about 2 mm/μs. Assuming that it has the same velocity as the polymer layer of thickness 106 μm, i.e. 2.08 mm/μs, Eq (11) was used to calculate the frequencies where minima of the reflection coefficient occurred. They are listed in Table 4, together with the experimental results deduced from Fig. 8 which is a plot of the reflection coefficient versus frequency.

The two experimental frequencies agreed with the results of the theoretical calculation to within 5%. The theoretical and experimental phase of the reflection coefficient of the 69 μm thick polymer layer are plotted in Fig. 9.

![Fig. 6. The experimental reflection coefficient where the polymer layer is 106 μm thick.](image-url)
Fig. 7. Theoretical results (solid line) and experimental data (*) of the phase of the reflection coefficient where the polymer layer is of thickness 106 μm.

Table 3. Frequency minima of the 106 μm thick polymer layer

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Theory</th>
<th>Expt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>9.81</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>19.62</td>
<td>19.63</td>
</tr>
<tr>
<td></td>
<td>29.43</td>
<td>29.01</td>
</tr>
</tbody>
</table>

Table 4. Frequency minima of the 69 μm thick polymer layer

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Theory</th>
<th>Expt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>14.49</td>
<td>13.80</td>
</tr>
<tr>
<td></td>
<td>28.98</td>
<td>28.51</td>
</tr>
</tbody>
</table>

Fig. 8. The experimental reflection coefficient where the polymer layer is of thickness 69 μm.
DISCUSSION AND CONCLUSION

A contact method employing a single broadband transducer bonded to a buffer rod was used to determine the acoustic velocity of a thin material layer. The measured reflection pressure amplitude experienced various maxima and minima. The minima, which were cusp-like, could be used to determine the velocity of the thin layer. While the frequency values agreed to within 5% of the theoretical results, the reflection amplitude at the minima were much higher than those of the theoretical results. Furthermore, the experimental phase at the minima did not agree with the phase of the theoretical calculation. It should be noted that the experimental condition did not exactly simulate the condition of the theoretical model. The model assumed a continuous incident wave while a pulse of finite duration was used in the experiment. Also, ultrasonic attenuation in the thin layer was not considered in the model. However, as the experimental frequency minima agreed with the results of the theoretical calculation to within 5%, the minima could be used to calculate the velocity of the thin layer, providing the thickness of the layer was known.

REFERENCES