Water-Based Couplants for General Purpose Use for Ultrasonic NDT Applications

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Revised received: 12 November 1999; accepted: 07 June, 2000

A study on the newly developed couplant liquid and gel suitable for ultrasonic NDT inspection is reported. Results of the measurements of various physical parameters like viscosity, density, ultrasonic velocity, etc. which have direct influence on acoustic coupling, are reported. With the help of the measured ultrasonic velocity and the acoustic impedance of the newly developed couplants, the results have been discussed along with theoretical considerations. It is indicated that the newly developed couplants have better transmission coefficient and give 3 dB better coupling, as compared to the conventionally used liquids. These couplants offer many other advantages and have potential applications in industry.

Introduction

The application of ultrasonic non-destructive testing (NDT) techniques is increasing continuously. In the direct contact methods of inspection, if there is a slight air gap between test object and the probe head, a high loss of energy occurs. In fact, in many cases, the loss is so enormous that no energy seems to be entering the job under the inspection. To overcome this problem, an intermediate liquid is generally used between the test object and the probe head; it is known as 'couplant'. It provides the acoustic coupling between the probe head and the test job. Ultrasonic NDE is also used for the testing of concrete, stones, timber and civil structures for finding materials characteristics, detection of defects and thickness measurements. Studies in the area of archaeology for the evaluation of ancient structures using ultrasonics have yielded valuable information.

A variety of liquids such as water, glycerin, oils of different viscosity, etc. are used for coupling purposes. Certain characteristics of the couplant liquid play an important role in the ultrasonic NDT evaluation, as the degree of the acoustic coupling depends upon the nature of the liquid also. Generally, some thicker oils and greases are preferred for use on vertical or rough surfaces and for inspection at higher temperatures.

With increase in the ultrasonic NDT applications, the consumption of petroleum products used as couplants is also increasing. On the other hand, there is a continuous increase in the price of oils and other petroleum products, which causes extra burden on foreign exchange expenses. In addition, use of oils and greases is not only too messy for the inspection of concrete, refractory bricks, stones, timber and other civil structures, it may also leave marks which may be difficult to remove afterwards. This situation calls for an alternative liquid, which should be free from these shortcomings and may be used as a suitable ultrasonic couplant. In this paper, the properties of a good acoustic couplant for ultrasonic NDT work, along with the working conditions and job under inspection have been described.

In this article, studies on two newly developed, water-based ultrasonic couplants — Sonotrac (V1 and V2) — have been reported. Although in many advanced countries similar liquids are in use, no such couplant is available in India so far. These couplant liquids show about 3-5dB better coupling than oil. The various physical properties such as density, viscosity, sound velocity and acoustic impedance of the liquids used as couplant have been compared with the measured values for the newly developed couplants. An attempt has been made to evaluate the coupling performance on the basis of the observed
values of acoustical impedance. The salient features of the developed couplants have also been spelled out.

**Theoretical Considerations**

If an ultrasonic beam is allowed to impinge on an interface of two media, Medium 1 and Medium 2, some of its energy is reflected and some is transmitted and scattered at the interface. If the acoustic impedance of the two media be: \( Z_1 = \rho_1 C_1 \) and \( Z_2 = \rho_2 C_2 \), where \( \rho \) and \( C \) are density and ultrasonic velocity in the two media, the acoustic pressure transmission coefficient (T) is expressed by the relation (1):

\[
T = \left( \frac{2\rho_2 C_2}{(\rho_2 C_2 + \rho_1 C_1)} \right) = 2Z_2 / (Z_2 + Z_1) \quad \ldots (1)
\]

and the acoustic pressure reflection coefficient R is given by Eq. (2):

\[
R = \left( \frac{\rho_2 C_2 - \rho_1 C_1}{(\rho_2 C_2 + \rho_1 C_1)} \right) = (Z_2 - Z_1) / (Z_2 + Z_1) \quad \ldots (2)
\]

The attenuation of sound due to scattering, spreading, diffraction and other mechanisms takes place only after the acoustic energy enters the second medium. The important part is how much energy is transmitted. In this, if all other parameters are kept the same, the two factors that play major role are: (i) the coupling condition between the surface of the job and probe head, and (ii) the acoustic impedance of probe face material \( Z_1 \), the coupling liquid \( Z_2 \), and the job under test \( Z_3 \).

In order to transmit the ultrasonic energy efficiently into the job under test, it is desirable to minimise the losses at the transducer and job interface. The optimum transmission of acoustic pressure can be obtained by using a matching layer of suitable thickness and characteristic impedance, included between the transducer and the load. For simplicity, let us assume that ultrasound is incident at right angles to the boundaries of three media having the characteristic impedance \( Z_1 \), \( Z_2 \), \( Z_3 \) respectively (Figure 1). It can be shown that ratio of the intensity transmitted through medium 3 to that incident on layer 1 is given by Eq. (3).

\[
I_3 / I_1 = 4Z_1 Z_3 / [(Z_1 + Z_3)^2 \cos^2 k_2 l_2 + (Z_2 + Z_3)^2 / Z_2]^2 \sin^2 k_2 l_2] \quad \ldots (3)
\]

where \( k_2 = 2\pi / \lambda_2 \) is the propagation constant of medium 2 (\( \lambda_2 \) is the wavelength) and \( l_2 \) is the thickness of the second medium.

If \( I_3 / I_1 = (2n-1)\lambda_2 / 4 \) and \( Z_2 = (Z_1 Z_3)^{1/2} \)

then one gets \( I_3 / I_1 = 1 \)

This means that if \( Z_1 \) is the acoustic impedance of the material of the transducer and \( Z_3 \) is that of the loading medium, then to obtain complete transmission from one medium to another of different characteristic impedance, the matching layer \( Z_2 \) must be an odd integral number of quarter wavelengths thick and should have a characteristic impedance equal to the geometric mean of the other two. In practice, it is difficult to keep thickness of the liquid couplant at a predetermined value. A thin layer of the couplant less than quarter wavelength is therefore used in practice.

For a very thin layer having \( l_2 << \lambda_2 \), the intensity transmission coefficient \( I_3 / I_1 \) would again be unity in Eq. (3). However, in practice, the couplant layer generally remains a finite fraction of \( \lambda_2 \) due to the roughness of the interfaces and the viscosity of the couplant. Therefore, it can be seen, according to Eq. (3), that the second term would dominate over the first term, \( Z_3 \) being much smaller than \( Z_1 \) or \( Z_2 \). Intensity transmission coefficients in this approximation can be given by expression (4).

\[
I_1 / I_1 \equiv 4 Z_2^2 (k_2 l_2)^2 / Z_1 Z_3 \equiv T_1^2 (k_2 l_2)^2 / (Z_4 / Z_5) \quad \ldots (4)
\]

where \( T_1 \) is the acoustic pressure transmission coefficient at interface 1 (Figure 1). Thus, as far as the acoustic parameters of the couplant are concerned, the intensity transmission coefficient \( I_3 / I_1 \) would depend on the factor \( T_1^2 \), the couplant thickness remaining unchanged.

**Experimental**

The measurements of density, viscosity and ultrasonic velocity have been carried out at room temperature using the developed liquid/Sonotrac \( V_1 \) and \( V_2 \). The specific gravity bottle method\(^{11}\) was used for the density measurements. The Stokes method of falling sphere\(^{12}\) was used for the viscosity measurements.

The ultrasonic velocity in the couplant liquids was measured at 2 MHz, using an ‘Ultrasonic
Interferometer' developed at National Physical Laboratory, New Delhi. Water was kept circulated around the measuring cell to keep the temperature constant. A set of readings were taken to check reproducibility of the results.

**Results and Discussions**

The measured values of the various parameters for the developed couplant liquid V₁ and V₂ along with those of water, glycerin (commercial grade) and oil are given in the Table 1. The similar parameters of some other common materials and some of the transducer materials are given under section A and section B, respectively in Table 2.

Let us now consider a case where a probe using a lead zirconate titanate (PZT) element is employed to examine a steel block, having a coupling medium in between them. Two interfaces, one between the transducer and coupling medium and the other between the coupling medium and steel block would appear. As an example, the calculated values of the transmission coefficient T₁ and T₂ for the two interfaces for various coupling liquids having PZT element probe at one end and steel block at the other are shown in Table 3, along with T₂, the intensity transmission factor.

It is evident from Table 3 that value of the intensity transmission or factor is highest for glycerin making it a very good coupling liquid on the basis of impedance matching considerations. At the same time, it is highly expensive to use glycerin for general purpose applications. The couplant liquids Sonotrac

![Figure 1](image-url)

**Table 1—Physical parameters of various liquid coupling materials**

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Couplant</th>
<th>Density ((\text{kg/m}^3)\times10^3)</th>
<th>Sound velocity (\text{m/s})</th>
<th>Acoustic impedance ((\text{kg/m}^2\text{s})\times10^4)</th>
<th>Viscosity (\text{cP})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water</td>
<td>1.00</td>
<td>1490</td>
<td>1.49</td>
<td>0.798</td>
</tr>
<tr>
<td>2</td>
<td>Sonotrac-V₁</td>
<td>1.12</td>
<td>1550</td>
<td>1.73</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>Sonotrac-V₂</td>
<td>1.15</td>
<td>1560</td>
<td>1.79</td>
<td>3500</td>
</tr>
<tr>
<td>4</td>
<td>Oil</td>
<td>0.90</td>
<td>1420</td>
<td>1.28</td>
<td>450</td>
</tr>
<tr>
<td>5</td>
<td>Glycerine</td>
<td>1.28</td>
<td>1920</td>
<td>2.49</td>
<td>620</td>
</tr>
</tbody>
</table>
Table 2 — Acoustical parameters of some common job-materials and transducer materials

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Material</th>
<th>Density (kg/m³) x 10³</th>
<th>Sound velocity (m/s)</th>
<th>Acoustic impedance (kg/m² s) x 10⁷</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aluminum</td>
<td>2.70</td>
<td>6320</td>
<td>1.706</td>
</tr>
<tr>
<td>2</td>
<td>Concrete</td>
<td>2.00</td>
<td>4600</td>
<td>0.920</td>
</tr>
<tr>
<td>3</td>
<td>Cast iron</td>
<td>6.90</td>
<td>3500</td>
<td>2.415</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>7.82</td>
<td>5850</td>
<td>4.574</td>
</tr>
<tr>
<td>5</td>
<td>Sandstone</td>
<td>1.90</td>
<td>2930</td>
<td>0.557</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Quartz</td>
<td>2.65</td>
<td>5740</td>
<td>1.521</td>
</tr>
<tr>
<td>7</td>
<td>Barium titanate</td>
<td>5.40</td>
<td>5100</td>
<td>2.754</td>
</tr>
<tr>
<td>8</td>
<td>Lead zirconate-titanate (PZT-5)</td>
<td>7.50</td>
<td>4000</td>
<td>3.00</td>
</tr>
<tr>
<td>9</td>
<td>Lithium sulphate (LiSO₄)</td>
<td>2.06</td>
<td>4720</td>
<td>0.972</td>
</tr>
<tr>
<td>10</td>
<td>Perspex</td>
<td>1.18</td>
<td>2730</td>
<td>0.322</td>
</tr>
<tr>
<td>11</td>
<td>Air</td>
<td>0.001</td>
<td>0330</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 — Calculated transmission parameters for interfaces of the coupling liquid with PZT element and steel block

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Coupling medium</th>
<th>T₁</th>
<th>T₂</th>
<th>T₁²</th>
<th>Viscosity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water</td>
<td>0.099</td>
<td>1.936</td>
<td>-20.1</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>Sonotrac V₁</td>
<td>0.115</td>
<td>1.927</td>
<td>-18.8</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>Sonotrac V₂</td>
<td>0.119</td>
<td>1.924</td>
<td>-18.5</td>
<td>3500</td>
</tr>
<tr>
<td>4</td>
<td>Oil</td>
<td>0.085</td>
<td>1.945</td>
<td>-21.4</td>
<td>450</td>
</tr>
<tr>
<td>5</td>
<td>Glycerin</td>
<td>0.166</td>
<td>1.896</td>
<td>-15.6</td>
<td>600</td>
</tr>
</tbody>
</table>

V₁ and V₂ are at the second and third positions. Similar values can be obtained with other materials of transducer elements and with different materials of the job under inspection. From the Table 3 one can see that even water is better than oil in transmitting the energy (~ T₁²) into the job, but it suffers from the defect that its viscosity is very low. A brief description of the salient features of these newly developed couplants is given below:

**Salient Features**

- Studies show that the newly developed couplants provide 3 dB better coupling as compared to other conventional couplants.
- These couplants do not contain any cellulose or petroleum products. It is designed as a reliable, stable and safe couplant for Ultrasonic Inspection on metals, FRP, timber, stone and concrete, etc.
- Being water-based and having wetting agents, Sonotrac wets various kinds of surfaces with equal ease and spreads faster and in a better way.
- These have water washable properties which are advantageous to the users as the clothes, hands, etc. are not messed or stained by their use.
- These do not interfere with subsequent Dye Penetrant Inspections.
• These contain germicidal additives and pose no skin problems and have long shelf-life.
• These are pleasant smelling and light pink coloured liquids and pose no fire hazards.

A good amount of work has been published on the thickness of couplant film in between the transducer and the job and on the possible error \(^{14,15}\) introduced by the coupling layer in ultrasonic attenuation and velocity measurements. A uniform layer of couplant and the application of same amount of pressure every time is necessary for good reproducibility of results.

**Concluding Remarks**

A couplant plays a very important role in ultrasonic testing by improving the transmission of ultrasonic waves from the transducer into the job under inspection. The results of a recent survey\(^{16}\) show that a majority of people are using petroleum products as couplants such as oils and greases in their inspection work, whereas less than 8% only of the total respondents are using synthetic couplants. In fact, this trend needs to be reversed. Petroleum products are too precious and involve foreign exchange. In fact, it is a sort of misuse of these products and their use as couplants in NDT should be discouraged. Synthetic couplants like Sonotrac are now available in the country and some of them give even better coupling than the petroleum products.

The present study shows that the newly developed couplants provide 3dB better coupling as compared to grease and other petroleum products. These couplants being water-based offer a superior wetting ability and easy spreading on the surface. They offer many potential applications in the industry, too.

**Acknowledgment**

The author is thankful to Dr S K Jain, Scientist, National Physical Laboratory, New Delhi, for helpful discussions.

**References**