Theory and applications of high frequency broadband ultrasound via a thin layer in contact with a solid

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Abstract
This paper reviews the transmission of high frequency broadband ultrasound via a thin layer in contact with a solid. A large part of this article deals with the physics of the acoustic resonance in a material system comprising water, a thin layer and a solid. Generally, it is very difficult to maintain the continuity between the layer and the solid during transmission of the ultrasound. The dry-contact ultrasonic technique, where the air at the layer/solid interface has been evacuated, enables the transmission of high frequency broadband ultrasound via the interface and allows us to realize acoustic imaging without the sample getting wet. In this case, to realize high-resolution acoustic imaging of a solid sample, selection of the layer to be inserted is important, and the acoustic resonance phenomenon is used for this purpose. The dry-contact and conventional ultrasonic techniques and their respective inspection capabilities are compared in this article. Moreover, the acoustic resonance phenomenon is used to characterize layered media. The acoustic properties of a thin polymer film, i.e., the acoustic impedance, ultrasonic velocity and density, can be accurately determined, and any scattering sources, e.g., voids, etc., can be detected with high sensitivity using this technique. The thicknesses of coatings on both surfaces of a steel plate can also be precisely measured by observing the acoustic resonance phenomenon occurring in the ultrasonic transmission system.

Key words: Ultrasonic inspection, Thin layer, Dry-contact, Acoustic resonance, Acoustic properties

1. Introduction

For ultrasound passing through thin layered media, the coefficients of transmission and reflection are frequency dependent, with the coefficient of transmission having its maximum value at the resonant frequency, where the thickness of the layer is equal to a quarter wavelength, whereas the coefficient of reflection has its minimum value under these circumstances (Brekhovskikh, 1960). This phenomenon is known as acoustic resonance and is used in the design of efficient ultrasonic transducers (Desilets, et al., 1978), (Manthey, et al., 1992) and (Alvarez-Arenas, et al., 2001) and in the measurement and evaluation of layered media, e.g., the thickness or acoustic properties of metallic films on a substrate (Haines, et al., 1978), (Kushibiki, et al., 1982), (Ogi, et al., 2007), (Houze, et al., 1984), (Kawashima and Wright, 1992), (Takagaki, et al., 2002), (Maznev and Every, 2009), (Kimra, et al., 1994) and (Wang, et al., 2002), the thickness of lubricant-films between two solids (Dwyer-Joyce, et al., 2003) and the acoustic properties of polymer films placed in water (Kumar, et al., 1997).

The acoustic resonance phenomenon arises because of the mismatch between the acoustic impedances of three media where a layer is inserted between a first and third media. The phenomenon is observed provided that continuity of the interfaces between the media is maintained and remains fixed during the transmission of the ultrasound. Therefore, except in special cases, utilization of the acoustic resonance phenomenon is limited in practical situations because the above mentioned condition has to be satisfied. For example, the phenomenon can be observed using an air-coupled ultrasonic transducer (Álvarez-Arenas, et al., 2007). Also, it can be observed for a thin film firmly fixed to a substrate or for a film in water. If we can observe the acoustic resonance phenomenon of a thin film on a substrate without an adhesion layer, the applicability of techniques utilizing this phenomenon would be expanded. However, it is generally very difficult to
transmit ultrasound through solid/solid interfaces. The main reason for the difficulty is that such interfaces include air gaps which reflect the ultrasound.

To transmit the ultrasound via a solid/solid interface, the formation of air gaps needs to be avoided. Drinkwater et al. examined the acoustic coupling between a rubber membrane and the resin plates having various surface roughness (Drinkwater, et al., 1997), which were examples of the solid/solid interfaces, and reported that a pressure of about 1 MPa was necessary at the rubber/plate interfaces to realize good acoustic coupling. The idea of introducing the pressure is highly valuable. To transmit high frequency broadband ultrasound through a thin layer into a solid sample, the dry-contact ultrasonic technique has been developed (Tohmyoh and Saka, 2002). In this technique, the air at the interface between the layer and the solid sample has been evacuated by a vacuum pump and a pressure of about 0.1 MPa is applied to the interface to improve the acoustic coupling at the layer/sample interface. Usually, a thin polymer film or thin rubber membrane is used for the thin layer and good acoustic coupling between such layers and the solid sample can be realized by selecting an appropriate material for the layer and using the special evacuation technique. The dry-contact ultrasonic technique enables us to realize high-resolution ultrasonic imaging in the sample without the sample getting wet (Tohmyoh and Saka, 2003). Also, the technique can be utilized for observations of the acoustic resonance phenomena at solid/solid interfaces (Tohmyoh, et al., 2006), something which has not yet been achieved otherwise.

In this review article, the theory of acoustic resonance in ultrasonic transmission systems, including those comprising solid/solid interfaces, and those utilizing the dry-contact ultrasonic technique to maintain the continuity at the solid/solid interface, is described. In the dry-contact ultrasonic technique it is imaging of the third medium that is of interest, whereas in the characterization of a layer utilizing the acoustic resonance phenomenon, the target medium is the second one.

![Fig.1. Ultrasonic transmission system comprising water, a thin layer and a solid sample.](image)

### 2. Theory of ultrasound transmitted through a thin layer

Let us consider the transmission of ultrasound in a material system comprising water, a thin layer and a solid sample as shown in Fig. 1. The ultrasound, which is emitted by an ultrasonic transducer, is reflected back from points within the sample and received by the same transducer. Here the sound pressure of the ultrasound emitted by the transducer is $P_I$ and that of the received ultrasound is $P_R$. The frequency spectrum of $P_R$ is given by

$$\varphi_R = \int_{-\infty}^{\infty} P_R \exp(-jwt) \, dt = \varphi_I \alpha_T t_{\text{WLS}} s_{\text{LSW}} D \psi,$$

where $\varphi_I = \int_{-\infty}^{\infty} P_I \exp(-jwt) \, dt$, $f = -1$, $f$ is the frequency, and $t$ time. $\alpha_T$ is a compound term for the ultrasonic attenuation in the system and is given by

$$\alpha_T = \exp \left(-2\left(\alpha_s l_s + \alpha_L d + \alpha_W l_W \right)\right),$$

where $\alpha_n$: $n = S, L, W$ are ultrasonic attenuation coefficients and the subscripts $S, L, W$ signify that the coefficient is for the solid sample, the thin layer and the water, respectively. $d$ is the thickness of the layer, $l_s$ the distance from the sample surface to the point in the sample from which the ultrasound is reflected, and $l_w$ the distance from the front edge of the transducer to the thin layer. $t_{\text{WLS}}$ is the transmission coefficient from the water to the sample via the layer and is given by (Brekhovskikh, 1960)
\[ t_{WLS} = \frac{4Z_SZ_L}{(Z_S - Z_L)(Z_L - Z_W)\exp(ik_Ld) + (Z_S + Z_L)(Z_L + Z_W)\exp(-ik_Ld)}, \]  

where \( Z_n \) (\( n = S, L, W \)) are the acoustic impedances in the solid, the thin layer and the water, respectively, \( k_L = 2\pi f / c_L \) is the wave number in the layer and \( c_L \) the sound velocity in the layer. Interchanging \( S \) and \( L \) in Eq. (3) gives the transmission coefficient from the sample to the water, \( t_{SLW} \). \( r_S \) is the reflection coefficient of the sample, which depends on the geometry and acoustic properties of the reflection source. For example, if ultrasound is reflected from the planar surface of the sample in air, it is given by

\[ r_{SA} = \frac{Z_A - Z_S}{Z_S + Z_A}, \]  

where \( Z_A \) is the acoustic impedance of air. \( D \) is a term representing the diffraction effect. \( \psi \) is a term expressing the signal loss at the layer/sample interface and is unity when there is no signal loss. To consider the effect of inserting a layer on the efficiency of the ultrasonic transmission, we determine the amplitude ratio

\[ \gamma = \frac{\phi_R}{\phi_R^0} = \frac{\theta \xi \psi}{1}, \]  

where \( \phi_R^0 \) is \( \phi_R \) without the layer (\( d = 0, \psi = 1 \)). \( \theta \) is a term related to the acoustic impedance matching and is given by the following expression (Tohmyoh, 2006)

\[ \theta = \left[ \cos^2(k_Ld) + A \sin^2(k_Ld) \right]^{-1}, \]

where

\[ A = \frac{(Z_WZ_S + Z_L^2)^2}{Z_L^2(Z_W + Z_S)^2}. \]

The maximum value of \( \theta \) is at the resonant frequency, \( f_R \), and is given by

\[ \theta_R = A^{-1}, \]

where

\[ f_R = \frac{c_L}{4d}. \]

The term \( \xi \) is the signal loss due to ultrasonic attenuation in the layer and is given by

\[ \xi = \exp \left( - \alpha_L d \right). \]

For the effective transmission of high frequency broadband ultrasound via a thin layer, it is very important to maintain the continuity between the layer and the sample surface, so that \( \psi \) should be close to unity. We deal with this important issue in the next section.

3. Dry-contact ultrasonic technique

3.1 Overview

Ultrasound is totally reflected at the interface between two solids in contact with each other. This is because there are usually air gaps at the solid/solid interface, and these air gaps reflect the ultrasound [Fig. 2(a)]. This phenomenon is utilized in detecting delamination and bonding failures in material systems. However, in general, this phenomenon is a problem for applications employing ultrasound, so the space between the ultrasonic transducer and the sample should be filled with liquid or a gel to nullify the problem of air gaps. Commonly, water is used for inspecting manufactured products [Fig. 2(b)], e.g., electronic packages, and the water enables an ultrasonic transducer to be scanned over the sample under test.
However, some products can be damaged by water, which limits the ultrasonic testing of such samples. To realize ultrasonic testing without the use of water, several techniques, e.g., the air-coupled capacitance transducer (Schindel, et al., 1995), (Alvarez-Arenas, et al., 2012), (Gan, et al., 2003), (Hutchins, et al., 2003), (Robertson, et al., 2002) and (Oralkan, et al., 2003), the electromagnetic acoustic transducer (Houck, et al., 1967), (Ludwig, et al., 1993), (Ogi, et al., 1995) and (Ogi, et al., 2001), laser ultrasound (White, 1963), (Rose, 1984), (Liu, et al., 2002), (Green, 2004) and (Arias and Achenbach, 2004), and microphone array (Chu, et al., 2014), (Rigelsford and Tennant, 2006) and (Brandes and Benson, 2007), have been proposed. Several megahertz broadband ultrasound can be transmitted and received by the air-coupled capacitance transducer (Alvarez-Arenas, et al., 2012) and the electromagnetic acoustic transducer (Ogi, et al., 1995), and this type of transducers are applicable for inspection of high temperature objects (Gan, et al., 2003). The lateral resolution for imaging can be enhanced by the use of the conical air-coupled capacitance transducer (Hutchins, et al., 2003), and the air-coupled capacitance transducer is suitable for surface imaging of the sample (Alvarez-Arenas, et al., 2001) and (Robertson, et al., 2002). Capacitive micromachined ultrasonic transducers with array structure are also realized for real-time imaging (Oralkan, et al., 2003).

These techniques can generate and receive the ultrasound in air, and can be used for the evaluation or testing of materials. However, at present, these techniques are limited in terms of their ability to transmit high frequency broadband ultrasound over several tens megahertz which is required for high-resolution ultrasonic imaging. The water immersion problem in ultrasonic testing might be solved by inserting a thin layer of a solid material between the water and the sample. However, in this case, the solid/solid interface between the layer and the sample is subject to the formation of air gaps, as described above, so the ultrasound is almost completely reflected back and does not reach the objective interface in the sample under test.

Drinkwater et al. reported a significant result that pressure applied to a rubber membrane/resin sample interface achieved good acoustic coupling at the interface (Drinkwater, et al., 1997). The pressure depended on the surface roughness of the resin sample and higher pressures were needed for rougher surfaces. For example, a pressure of around 1 MPa was required to realize good acoustic coupling between the membrane and a resin sample with a roughened surface. If the purpose of transmitting the ultrasound through the layer/sample interface, which is one of the solid/solid interface, is to enable inspection of an interface of the sample without the sample getting wet, it may be difficult to apply pressures as high as 1 MPa to such a solid/solid interface. Moreover, the sample might be broken by such high pressure.

The dry-contact ultrasonic technique has been proposed for transmitting high frequency broadband ultrasound through a solid/solid interface (Tohmyoh and Saka, 2002). In this technique a thin layer is inserted between the water and the solid sample. The key to this technique is (1) to evacuate the air between the thin layer and the solid sample, and (2) to select a thin layer through which the ultrasound is efficiently transmitted. The principle of the dry-contact ultrasonic technique is described in the next section.

![Fig. 2. Two ultrasonic transmission systems. (a) with a solid/solid interface. (b) with a liquid/solid interface.](image)

### 3.2 Principle

A photograph of the apparatus for the dry-contact ultrasonic technique is shown in Fig. 3 (Tohmyoh and Saka, 2003). The apparatus has a path control layer between the solid layer and the sample, and the path control layer has exhaust paths connected to a vacuum pump. The air between the solid layer and the sample is evacuated by the vacuum pump through the exhaust paths. The solid layer is firmly attached to the sample by evacuating the air between them. Here, if we use this apparatus in air a pressure of about 0.1 MPa is applied at the layer/sample interface because atmospheric
pressure is 0.1 MPa and the pressure between the layer and the sample is considered to be almost zero. Usually, a thin polymer film or rubber membrane is used for the layer. The vessel is then filled with water, and acoustic imaging can be performed using a scanning focused ultrasonic transducer immersed in the water.

The results of experiments in which ultrasound was transmitted into an acrylic resin sample via various solid layers showed that there was almost no signal loss at the layer/sample interface with either polyvinyl chloride (PVC) or polyethylene (PE) polymer films with thicknesses of around 10 μm (Tohmyoh and Saka, 2003). On the other hand, the efficiencies with which ultrasound was transmitted through 0.2 mm thick rubber membranes were between 20 and 70% of the theoretical value, indicating that reflection of the signal at the rubber membrane/sample interface related with incomplete coupling had occurred. From the experimental results, it is clear that thin polymer films are better for realizing high efficiency dry-contact ultrasonic transmission compared with the cases through relatively thick rubber membranes.

The acoustic image obtained using the dry-contact ultrasonic technique with a PVC film is shown in Fig. 4(a) and that obtained by the conventional water immersion technique is shown in Fig. 4(b). The sample is a ball-grid-array (BGA) package mounted on a printed circuit board (PCB) by solder joints with the surface of the package encapsulated in resin. Figure 4 shows that the joints between the package substrate and the solder balls are clearly imaged in both cases.

![Fig. 3. Details of the dry-contact ultrasonic unit (top). Schematic illustration of the dry-contact ultrasonic transmission system (bottom). Reprinted from (Tohmyoh, et al., 2009), copyright (2009), with permission from Elsevier.](image)

![Fig. 4. Acoustic images of the jointing interface between the package substrate and the solder balls obtained using (a) the dry-contact technique using a PVC film and (b) the water immersion technique. (from (Tohmyoh and Saka, 2003), © (2003) IEEE.](image)
Figures 5(a) and (b) show the echoes obtained using the dry-contact ultrasonic technique with a 9 μm thick polyvinylidene chloride (PVDC) film and that obtained using the conventional water immersion technique, respectively (Tohmyoh and Saka, 2004b). The sample is a flip chip package with a bare silicon chip. The echo from the surface of the chip obtained using the dry-contact technique is far smaller than that obtained using the water immersion technique. Figures 5(c) and (d) are the acoustic images of this package obtained using these two techniques. Both images clearly show that the bumps at the corner of the package are not bonded. Note that the gain of the receiver for the dry-contact ultrasonic technique was 8 dB lower than that for the water immersion technique. This is because the PVDC film works as an acoustic matching layer between the water and the silicon chip. This matching phenomenon is treated in the next section.

![Acoustic images](image_url)

**Fig. 5.** Examples of the echoes obtained under (a) dry-contact through a PVDC film and (b) water immersion. Acoustic images from beneath the silicon chip obtained with a 100 MHz ultrasonic transducer (The defective joints are indicated by the arrows): (c) Dry-contact through a PVDC layer, (d) using water immersion. Reprinted from (Tohmyoh and Saka, 2004b) with the permission of The Japan Society of Mechanical Engineers.

### 3.3 Selection of solid layer for inspection

In this section, we discuss the method by which the solid layer is chosen in order to get higher quality acoustic images of the sample under dry-contact conditions. The quality of the acoustic image is determined by the spatial resolution and the signal-to-noise ratio (SNR). Thus to get higher quality acoustic images, higher frequency ultrasound components need to be transmitted into the sample as efficiently as possible. As described in the previous section, because $\psi$ is unity for typical polymer films, the efficiency is governed by $\theta$ and $\xi$ from Eq. (5).

Figure 6 shows $\xi$ for the polymer films and rubber membranes as functions of $f$ (Tohmyoh, et al., 2009). The PVC and PVDC films are 9 μm thick, and the two rubber membranes are 0.2 mm thick. For example if we compare $\alpha_z$ in Eq. (10) at $f=40$ MHz, the values of $\alpha_z$ for the PVC, PVDC, and the soft and hard rubber are $-0.65 \times 10^5$, $-1.37 \times 10^5$, $-0.29 \times 10^5$ and $-0.56 \times 10^5$ dB/m, respectively, showing that the values of $\alpha_z$ for the two polymers are larger than those for
rubbers. However compared with the rubber membranes, thinner polymer films are easily obtained, so, for example, the 
values of $\xi$ for the thin polymer films, i.e., the 9 $\mu$m thick PVC and PVDC films, are so small as to be negligible as 
compared with those for the rubber membranes as shown in Fig. 6. Therefore, in the case of using typical polymer films, 
the efficiency is mainly due to the value of $\theta$.

Figure 7(a) shows $\theta_k$ as a function of $\zeta (= Z_S / Z_W)$ and $m (= Z_L / (Z_W Z_S)^{0.5})$ (Tohmyoh, 2006). The value of $\theta_k$ is 
greater than unity for $\zeta > 1$ and $\zeta^{0.5} < m < \zeta^{0.5}$, and the greater the mismatch between $Z_W$ and $Z_S$ gives the larger the value 
of $\theta_k$. For example, if the sample is Si (100) with $Z_S$ of 20.7 MNm$^{-3}$s, $\zeta = 13.7$ and $\theta_k$ is 3.9 at $m = 1$. Thus, $\theta_k$ is much 
larger than the value of $\xi$ for the thin polymer films discussed above. Figure 7(b) shows the behavior of $\theta$ as a function 
of the normalized frequency ($= f / f_k$) with $\theta_k = 3.0$. The value of $\theta$ is greater than 1 for $f / f_k$ between 0 and 2, and we 
notice that this has a similar characteristic to a band pass filter.

**Fig. 6.** Ultrasonic attenuation in the solid layers. Reprinted from (Tohmyoh, et al., 2009), copyright (2009), with permission 
from Elsevier.

**Fig. 7.** Concept of an acoustic matching polymer layer. (a) Distribution of $\theta_k$ as a function of the dimensionless parameters $\zeta$ 
and $m$. (b) Behavior of $\theta$ in the case where $\theta_k = 3.0$. Reprinted from (Tohmyoh, 2006) with the permission of the Acoustical 
Society of America.
From the above discussion, it is clear that a thin polymer film should be used for the high-resolution dry-contact ultrasonic technique. In particular, if testing a sample with high acoustic impedance, \( \theta \) should be chosen depending on the frequency characteristics of the ultrasonic transducer to be used. Note that \( \theta \) can be chosen by choosing appropriate values for the impedance, \( Z_t \), and thickness, \( d \), of the polymer film. In the following examples, the selections of thin solid layers depending on each particular sample are described.

The first sample was a 25 mm diameter, 2.1 mm thick disk with epoxy resin into which a 4.67 mm \( \times \) 3.52 mm \( \times \) 0.6 mm silicon chip had been embedded (Tohmyoh and Saka, 2004a). Ultrasound was transmitted from the silicon chip side, and the echo reflected from the silicon/epoxy resin interface was recorded using the dry-contact technique with a 9 \( \mu \)m thick PVDC film. In the case of this ultrasonic transmission system, the behavior of \( \theta \) was as shown in Fig. 7(b) and the value of \( f_R \) was 54.7 MHz. An example of the amplitude spectrum of the echo from the silicon/epoxy resin interface obtained with a 50 MHz ultrasonic transducer is shown in Fig. 8. Figure 8 clearly shows that the peak frequency, \( f_P \), of the amplitude spectrum obtained via the PVDC film is higher than that obtained without the film. This suggests that the film works as a frequency filter. Figure 9 shows a comparison between the amplitude ratio from the experimental results and the theoretical values determined from Eq. (5). Here in addition to the data obtained with the 50 MHz ultrasonic transducer, those obtained with 30 and 100 MHz ultrasonic transducers are added. The theoretical amplitude ratio gives reasonable agreement with the experimental data.

The second sample was a wafer-level package with a bare silicon chip already mounted on a PCB by a BGA assembly as shown in Figs. 10(a) and (b) (Tohmyoh and Saka, 2004a). The acoustic image shown in Fig. 10(c) was obtained by the dry-contact technique with a 9 \( \mu \)m thick PVDC film, and Fig. 10(d) was obtained using water immersion. The 100 MHz ultrasonic transducer was used. A defective joint can clearly be visualized in both acoustic images but the quality of the image is higher for the dry-contact technique. This is because the SNR of the image was increased by signal amplification due to the PVDC film working as a frequency filter.

![Fig. 8. Examples of the amplitude spectra of the echoes from a silicon/epoxy resin interface obtained using the 50 MHz ultrasonic transducer (from (Tohmyoh and Saka, 2004a), © (2004) IEEE).](image)

![Fig. 9. Comparison between the theoretical amplitude ratio and experimental ones using 30, 50 and 100 MHz ultrasonic transducers. The values of the signal modulation are shown as \( \Delta f_P \). (from (Tohmyoh and Saka, 2004a), © (2004) IEEE).](image)
Fig. 10. Examined wafer level package. (a) Whole view of the package mounted on a PCB. (b) Back view of the package before mounting. Acoustic images of the jointing interface beneath the silicon chip obtained using the 100 MHz ultrasonic transducer. (a) Dry-contact technique using a PVDC film. (b) Usual water immersion technique. The defective joint is indicated by the arrows (from Tohmyoh and Saka, 2004a), © (2004) IEEE).

Fig. 11. Acoustic images showing delamination between the encapsulating resin and the chip pad obtained using (a) the dry-contact technique with a PVC film and (b) water immersion. Reprinted from (Tohmyoh, et al., 2009), copyright (2009), with permission from Elsevier.

The third sample was an encapsulated resin package containing areas where delamination of the encapsulating resin from the chip pad had occurred (Tohmyoh, et al., 2009). Because the acoustic impedance of the resin is much lower than that of silicon and relatively close to water, we selected the layer from the viewpoint of the ultrasonic attenuation in the layer. For this application, we selected a 9 μm thick PVC film. The acoustic image obtained by the dry-contact ultrasonic technique using this film is shown in Fig. 11(a) and that obtained using water immersion is shown in Fig. 11(b). The dry-contact image clearly shows the areas of delamination, indicated by the arrows. On the other hand, the contrast in the water immersion image is much less because the package has been invaded by water.

3.4 Rubber coupling technique

Because rubber membranes are ductile and have stable elongation, it is expected that they would be practical layers for repeated measurements using the dry-contact ultrasonic technique. However, as reviewed in this paper, the quality of the acoustic images obtained using rubber membranes were far inferior compared with those obtained using polymer
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films. The reason for the low transmission efficiency via rubber membranes is the large signal loss at the rubber membrane/sample interface in addition to high attenuation in the membrane.

An investigation to find a rubber membrane suitable for repeated measurements using the dry-contact ultrasonic technique was undertaken (Tohmyoh and Akaogi, 2007). Four kinds of rubber membrane, denoted R1, R2, R3 and R4, were prepared, each with a thickness of 0.2 mm. The Young's moduli of R1, R2, R3 and R4, which were measured to characterize the softness of the membrane, were 9.6, 7.7, 3.1 and 0.9 MPa, respectively. The value of $Z_L$ for the four membranes were in the range from 2.24 to 2.55 MNm$^{-3}$s, and the values of $\rho_L$ and $c_L$ of the membranes were in the range from 1116 to 1218 kg/m$^3$ and from 1977 to 2117 m/s, respectively. The value of $\xi$ for R4 was the largest (the smallest ultrasonic attenuation in the membrane), while that for R1 was the smallest. Figure 12 shows $\gamma$ at the rubber membrane/acyrylic resin interfaces, which shows that good acoustic coupling was achieved with the R4 membrane. Because, in addition to a large value of $\xi$, the R4 membrane has the largest values of $\gamma$ it would make a practical membrane for dry inspection.

Acoustic images of the sample used previously for the images in Fig. 11 obtained using the R4 and R1 membranes are shown in Fig. 13(a) and (b), respectively. Although the acoustic image obtained with the R1 membrane is poor, that obtained with the R4 membrane is of sufficient quality to visualize the delaminated areas in the package. The acoustic images were repeatedly recorded 100 times using the R4 membrane without the membrane breaking.

3.4 Performance of the dry-contact ultrasonic technique for inspection

The quality of the acoustic image is mainly determined by the spatial resolution and the SNR, which can be traded-off with each other. The lateral resolution, $d_{PE}$, is defined by the separation between two sound sources and can be determined from the effective point spread function as follows (Bechou, et al., 1997) and (Canumalla, 1999):

$$g_E = \int g \varphi df,$$

(11)
and
\[
g = \left[ \frac{2J_1(B)}{B} \right]^2, \tag{12}
\]
where \( J_1 \) is a Bessel function of the first kind and first order, \( B = k_w r a / z_0 \), \( k_w \) is the wave number in water, \( c_w \) the sound velocity in water, \( r \) the distance from the central axis of the ultrasonic transducer, \( z_0 \) the focal length, and \( \phi \) the amplitude spectrum of the echo reflected from the objective interface. An example of \( g_E \) for a 100 MHz focused ultrasonic transducer with \( 2a \) of 6.35 mm and \( z_0 \) of 12.7 mm is shown in Fig. 14 (Tohmyoh and Saka, 2004b). Here \( \phi \) is obtained from the silicon/acrylic resin interface using a PVDC film. From \( g_E \), \( d_{\text{PE}} \) can be determined using the following relationship:
\[
g_E(0) = 2g_E\left(d_{\text{PE}}/2\right)^2 + g_E\left(d_{\text{PE}}\right) = 0. \tag{13}
\]
From Fig. 14, \( d_{\text{PE}} \) is found to be 49 \( \mu \)m and this is almost the same as that achieved using conventional water immersion with the same focused ultrasonic transducer \( (d_{\text{PE}} = 47 \mu \text{m}) \). Although the value of \( d_{\text{PE}} \) is almost unchanged when using the thin polymer film, in the case of the dry-contact technique with a rubber membrane, the value of \( d_{\text{PE}} \) is 30% greater than that of the water immersion case (Tohmyoh and Akaogi, 2007). This is due to the larger ultrasonic attenuation in the rubber membrane, especially at the higher frequency components.

Another important feature of ultrasonic inspection is the ability to detect narrow gaps. For example, in the case of very narrow gaps, the surfaces are likely to come into contact with each other due to elastic deformation arising from the transmission of the ultrasound, making such gaps difficult to detect. Recently, this has been confirmed experimentally (Tohmyoh and Akanda, 2006).

Two silicon chips with dimensions of 20 mm \( \times \) 20 mm \( \times \) 0.5 mm were bonded by the direct bonding technique and circular patterns with diameters of 5 to 1000 \( \mu \)m and depths of 4 or 140 nm were introduced on the surface of one of the chips to be bonded, see Fig. 15(a). Figures 15(b) and (c) are the acoustic images obtained with a 30 MHz focused ultrasonic transducer and Figs. 15(d) and (e) were obtained using a 100 MHz focused ultrasonic transducer. The gaps in the sample shown in Figs. 15(b) and (c) are 140 nm deep and those shown in Figs. 15(c) and (e) are 4 nm deep. The value of \( d_{\text{PE}} \) for the 30 MHz transducer was estimated to be 165 \( \mu \)m and that for the 100 MHz transducer was 48 \( \mu \)m.

In the case of 140 nm gaps, circles with diameters greater than \( d_{\text{PE}} \) can clearly be identified for both transducers. On the other hand, for 4 nm gaps, the circles with diameters of 500 and 600 \( \mu \)m are unclear with the 30 MHz transducer, although these are clearly visible using the 100 MHz transducer. As mentioned above, the diameters of these circles are greater than \( d_{\text{PE}} \). It is clear that the surfaces have come into contact with each other as a result of the transmission of the ultrasound and the ability to detect the gaps has decreased. Thus, the ability to detect narrow gaps is governed by both the depth and diameter of the gap. The three-dimensional features of the defect should also be considered in discussing the detection of defects.

Fig. 14. Effective point-spread function for the 100 MHz ultrasonic transducer in the case of dry-contact through a PVDC film (a. u.). Reprinted from (Tohmyoh and Saka, 2004b) with permission from The Japan Society of Mechanical Engineers.

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Fig. 15. Acoustic images of nanometer sized gaps embedded in a 4.5 mm × 4.5 mm Si [100] chip. (a) Gap pattern and a cross section through the sample. The images in (b) and (c) were obtained with the 30 MHz ultrasonic transducer and those in (d) and (e) were obtained with the 100 MHz ultrasonic transducer. The height of the gap for the images in (b) and (d) was 140 nm, and that for the images in (c) and (e) was 4 nm. Reprinted from (Tohmyoh and Akanda, 2009) with permission from the Acoustical Society of America.

4. Evaluation of thin layers

In section 3, it was shown that the intensity of the ultrasound is increased by the insertion of a polymer film due to acoustic resonance in the system comprising water, the film and the sample. This acoustic resonance phenomenon can be used to characterize layered media. For example, the acoustic properties of polymer films (Tohmyoh, et al., 2006) and the thicknesses of coatings can be measured using the acoustic resonance phenomenon (Tohmyoh and Suzuki, 2009), (Tohmyoh, et al., 2012) and (Sunaga, et al., 2013). Moreover, highly sensitive detection of defects in layered media can be achieved using this phenomenon (Tohmyoh and Ikarashi, 2013).

4.1 Acoustic properties

Generally, the crystalline structure of polymer materials are affected by a number of process variables, e.g., temperature, pressure, rheological history, etc. Polymer materials have been characterized using ultrasound and it is the acoustic properties of materials, such as the acoustic impedance, ultrasonic velocity, ultrasonic attenuation, and so on, that have been used for such purposes. Although bulk polymers can be characterized by conventional ultrasonic testing, the technique can hardly be applied to polymer films less than 10 µm thick. In this section, we describe the use of the acoustic resonance phenomenon to precisely measure the acoustic properties of thin polymer films. Several techniques for simultaneously determine the ultrasonic velocity and the materials thickness for relatively thick. metallic or polymer plate (Dayal, 1992), (Kim, et al., 2003), (Alvarez-Arenas, 2010) and (Loosvelt and Lasaygues, 2011). The sound velocity and thickness of relatively thin specimen can be measured by time-resolved acoustic microscopy (Hänel, 1998). Kumar, et al. successfully determined the acoustic impedance of a 20 µm thick polyethylene terephthalate (PET) film, where the
The frequency dependence of the echo transmitted via the film in water was used (Kumar, et al., 1997). The technique is a valuable tool for determining the acoustic impedance of free-standing polymer films. However, the accuracy in determining the acoustic impedance might decrease for films with lower acoustic impedance because the frequency dependence of the echo becomes more evident for ultrasonic transmission systems with larger mismatch between the acoustic impedances of the composite media.

To determine the acoustic properties of a thin film, we consider the ultrasonic transmission system with larger mismatch of the acoustic impedances and the system is comprising water, a thin film and a reflecting plate. Here the ultrasound emitted by the ultrasonic transducer is transmitted through the system and the echo reflected from the back of the plate is received by the same ultrasonic transducer. The amplitude ratio for this transmission system with the thin film to that without the thin film is given by Eq. (5). If the ultrasonic attenuation in the layer can be ignored (\( \xi = 1 \)) and there is no signal loss at the film/reflection plate interface (\( \gamma = 1 \)), \( \gamma_W \) is equal to \( \theta_R \) at \( f_R \). Under these assumptions, from Eqs. (7) and (8), we get the following quadratic equation in \( Z_L \) (Tohmyoh, et al., 2006):

\[
Z_L^2 - BZ_L + Z_WZ_B = 0, \tag{14}
\]

where

\[
B = \frac{Z_W + Z_B}{\sqrt{\gamma_R}}, \tag{15}
\]

and \( Z_B \) is the acoustic impedance of the reflecting plate. By solving Eq. (15), we get

\[
Z_L = \frac{B - \sqrt{B^2 - 4Z_WZ_B}}{2}. \tag{16}
\]

Also, from Eq. (9),

\[
c_L = 4df_R. \tag{17}
\]

The density of the film is given by

Fig. 16. Results of the frequency analysis. (a) Amplitude spectra of the back-wall echoes from the tungsten plate with and without a polymer film. (b) Amplitude ratio. Reprinted from (Tohmyoh, et al., 2006) with permission from The American Institute of Physics.
\[
\rho_L = \frac{Z_L}{c_L}.
\]  

(18)

From Eqs. (16) to (18), the three parameters \(Z_L, c_L\) and \(\rho_L\) can be determined provided that \(\gamma_R\) and \(f_R\) are measured and \(d\) is known in advance.

Figure 16(a) shows the amplitude spectra in cases with and without a polymer film. The films tested were an 8 \(\mu\)m thick PVC film and a 12 \(\mu\)m thick LDPE film. Because the acoustic resonance phenomenon can be observed more clearly with a reflecting plate with higher acoustic impedance, a tungsten plate \((Z_B = 99.84 \text{ MNm}^{-3}\text{s})\) was used in the experiments. The amplitude spectra obtained with these films are greater than that without the film, suggesting that acoustic resonance had occurred with these films in the system. The amplitude ratios are plotted in Fig. 16(b), from which the values of \(\gamma_R\) can be obtained. From the measured values of \(\gamma_R\) and \(f_R\), the values of \(Z_L, c_L\) and \(\rho_L\) for the PVC film were determined to be 1.89 \(\pm\) 0.01 MNm\(^{-3}\)s, (2.06 \(\pm\) 0.03) \(\times\) 10\(^3\) m/s and (0.92 \(\pm\) 0.02) \(\times\) 10\(^3\) kg/m\(^3\), respectively. The values for the LDPE film were 2.35 \(\pm\) 0.01 MNm\(^{-3}\)s, (1.75 \(\pm\) 0.01) \(\times\) 10\(^3\) m/s and (1.35 \(\pm\) 0.02) \(\times\) 10\(^3\) kg/m\(^3\), respectively. The validity of the measurement was demonstrated by measuring \(\rho_L\) with an electronic force balance.

It is noted that optical microscope images of the polymer film can be acquired together with the acoustic properties of the film if a transparent glass plate is used instead of the tungsten plate. This acoustical-optical hybrid technique is very useful for monitoring changes in the crystalline structure of polymer films (Tohmyoh and Sakamoto, 2014).

4.2 Detection of defects

In the previous section, we described measurements of the acoustic properties of a polymer film under the assumption that ultrasonic attenuation in the film can be ignored. This assumption is valid for a thin, uniform polymer film. However, it is invalid if there are any scattering sources within the film. Assuming \(\psi\) is unity, from Eq. (5), \(\xi\) at \(f_R\) is given by

\[
\xi = \frac{\gamma_R}{\theta_R}.
\]  

(19)

Figure 17 shows the values of \(\xi\) for a 6 \(\mu\)m thick PVC film and a 13 \(\mu\)m thick PVDC film. Generally, the value of \(\xi\) for thin polymer films is close to unity and that of the PVC film is around unity. On the other hand, the value of \(\xi\) for the PVDC film is far smaller than unity. This experimental result suggests that there are scattering sources in the film. Actually, some micro-bubbles were observed on a cross section of the film. It is noted that this technique measures \(\xi\) at \(f_R\) where \(\gamma\) and \(\theta\) take their maximum values and this contributes to precise measurements of \(\xi\).

![Fig. 17. (a) Decibel representation of \(\xi\) for the PVC and PVDC films. (b) Cross-sectional micrograph of a PVDC film with randomly located micro-bubbles, which might act as scattering sources for acoustic waves. Reprinted from (Tohmyoh and Ikarashi, 2013) with permission from The Japan Society of Applied Physics.](image_url)
4.3 Measurement of coating thickness

In this section, we describe measurements of the acoustic resonance phenomenon for a polymer coated steel plate, which are used to find the thicknesses of the coatings on both sides (Tohmyoh, et al., 2012). Both surfaces of the plate are covered with coatings and the continuity at the interfaces between the coating and the plate are always maintained. The thickness of the top coating is $d_S$ and that of the back coating is $d_B$. Ultrasound is transmitted by the ultrasonic transducer and the echo reflected from the back of the plate is recorded [Fig. 18(a)]. The amplitude ratio for the case with the coating ($\varphi_B$) to that without the coating ($\varphi_B^0$) is given by (Tohmyoh, et al., 2012)

$$\frac{\varphi_B}{\varphi_B^0} = \frac{T_S}{r_B} \frac{r_B^0}{r_B^0},$$

where $T_S$ is the echo transmittance from the water into the plate and $r_B$ the reflection coefficient from the back of the plate, and these are given by

$$T_S = \frac{4Z_W Z_P / (Z_W + Z_P)^2}{\cos k_C d_S + i (Z_W Z_P + Z_C^2 / (Z_W + Z_P) \sin k_C d_S)},$$

$$r_B = \frac{\left(Z_P / Z_A - 1\right) + i \left(Z_P / Z_C - Z_C / Z_A\right)}{\left(Z_P / Z_A + 1\right) + i \left(Z_P / Z_C + Z_C / Z_A\right)} \tan k_C d_B,$$

where $Z_A$ is the acoustic impedance of air. The ratio $\varphi_B / \varphi_B^0$ has two extreme values. The frequencies where the $\varphi_B / \varphi_B^0$ have maximum and minimum values are denoted as $f_{\text{max}}$ and $f_{\text{min}}$, respectively. The values of $d_S$ and $d_B$ can be determined from $f_{\text{max}}$ and $f_{\text{min}}$ using the following relationships

$$d_S = \frac{c_C}{4 f_{\text{max}}},$$
The steel samples were 20 mm × 20 mm and both surfaces were covered with coatings. A 100 MHz ultrasonic transducer was employed in the experiments. Figures 18(b) and (c) show examples of the amplitude spectra ($\phi_0$, $\phi_0'$) and the amplitude ratio ($\phi_0 / \phi_0'$). Here #1 is the sample number. Sample #R1 is the same sample as sample #1 but was reversed for the test. Although the two amplitude spectra are different, the peak frequencies ($f_{max}$ and $f_{min}$) are coincident with each other. A total of 24 samples were evaluated using this technique and the results are summarized in Figs. 19(a) to (c). Here, $d^E_S$ and $d^E_B$ are the thicknesses of the top and bottom coatings found using this technique, and $d^O_S$ and $d^O_B$ are those measured by direct observation with an optical microscope to the cut samples. For all the combinations of $d_S$ and $d_B$, the values of $d^E_S$ and $d^E_B$ are in good agreement with those of $d^O_S$ and $d^O_B$, and the validity of the present technique is verified. Figure 19(d) shows $d^E_B / d^E_O$ vs. $d^O_B / d^O_O$ and we found the thickness of the top coating did not affect the measurement of the thickness of the bottom coating.

Moreover, by mapping the resonant frequency for the coated steel plate using a focused ultrasonic transducer, the distribution of the thickness of the coating can be obtained (Sunaga, et al., 2013). Figure 20 shows this distribution for bottom coating to be in the range from 12 to 16 $\mu$m thick, and the results are in good agreement with the thickness profile obtained from cross-sectional measurements. Although Eq. (24) was based on the plane wave theory, it was experimentally confirmed that Eq. (24) was also applicable for the focused ultrasonic transducer.

5. Conclusions

In this paper, we treated the transmission of high frequency broadband ultrasound through a thin layer and into a solid sample. The ultrasonic transmission system comprises water, the thin layer and the solid sample, and the acoustic resonance phenomenon occurs in this multi-layered system. First, we described how to remove air gaps from the interface between the thin layer and the solid sample using a vacuum system. After evacuating the air from the interface between the sample and a polymer film we demonstrated the efficient transmission of ultrasound via the interface. This technique is called the dry-contact ultrasonic technique. The technique was used for the acoustic imaging of defects, i.e., delamination and bonding failures, in various types of electronic components while keeping the samples dry. For high-resolution dry-contact acoustic imaging, the acoustic resonance phenomenon in the ultrasonic transmission system is also applicable.
Fig. 20. Demonstration of acoustic resonant imaging. (a) Photograph of the back side of the sample. The square shows the imaging area. (b) The acoustic resonance image. (c) The distribution of the coating thickness. (d) Cross-sectional view on the line A-A in (c) obtained with an optical microscope. (e) Thickness profile on the line A-A in (c) obtained using the present method. Reprinted from (Sunaga, et al., 2013), copyright (2013), with permission from Elsevier.

Secondly, we used the acoustic resonance phenomenon for characterizing layered media. The acoustic impedance, ultrasonic velocity and density of thin polymer films with thicknesses of around 10 μm were determined by observing and analyzing the acoustic resonance phenomenon in systems comprising water, the polymer film and a metal reflecting plate. It was noted that small defects in the film such as micro-bubbles can also be detected using the same ultrasonic transmission system. Moreover, we showed that the thicknesses of coatings on the top and bottom surfaces of a steel plate can be measured simultaneously by recoding the echo reflected from the back surface of the plate.

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Appendix A. Nomenclature

\( c_C \): sound velocity in the coating
\( c_L \): sound velocity in the layer
\( c_W \): sound velocity in water
\( D \): term representing the diffraction effect
\( d \): thickness of the layer
\( d_{PE} \): lateral resolution
\( d_t, d_b \): thickness of top and bottom coatings
\( f \): frequency
\( f_{\max}, f_{\min} \): frequencies were \( \varphi_B / \varphi_B^0 \) takes maximum and minimum values
\( f_P \): peak frequency
\( f_R \): resonant frequency
\( g, g_0 \): point spread function and effective point spread function
$J_1$: Bessel function of the first kind and first order  
$k_C$: wave number in the coating  
$k_L$: wave number in the layer  
$k_W$: wave number in water  
$l_S$: distance from the sample surface to the reflection source in the sample  
$l_W$: distance from the front edge of the ultrasonic transducer to the thin layer  
$P_R$, $P_I$: sound pressure of the ultrasound received and emitted by the ultrasonic transducer  
$r$: distance from the central axis of the ultrasonic transducer  
$r_n$: reflection coefficient at the back of a plate with both sides coated  
$r_S$: reflection coefficient of the sample  
$r_{SA}$: reflection coefficient between the sample and air  
$t$: time  
$T_S$: echo transmittance from the water into the plate with both side coating  
$t_{SLW}$: transmission coefficient from the sample into the water via the layer  
$t_{WLS}$: transmission coefficient from the water into the sample via the layer  
$z_0$: focal length of the ultrasonic transducer  
$Z_A$: acoustic impedance of air.  
$Z_B$: acoustic impedance of back plate  
$Z_{PL}$, $Z_{CL}$, $Z_{CW}$: acoustic impedances of the steel plate and the coating  
$Z_S$, $Z_L$, $Z_W$: acoustic impedances for the sample, the layer and the water  
$\alpha_S$, $\alpha_L$, $\alpha_W$: ultrasonic attenuation coefficient of the sample, the layer and the water  
$\gamma$: amplitude ratio  
$\gamma_k$: $\gamma$ at $f_R$  
$\phi_n$, $\phi_0$: amplitude spectra of the echoes from the back of the steel plate in the cases with and without coatings on both surfaces of the plate  
$\phi_n^0$: $\phi_n$ for $d = 0$ and $\psi = 1$  
$\theta$: term related to the acoustic impedance matching  
$\theta_k$: maximum value of $\theta$  
$\rho_L$: density of the layer  
$\xi$: signal loss due to ultrasonic attenuation in the layer  
$\psi$: signal loss at the solid/solid interface in the ultrasonic transmission system

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