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# Excitation of Plate Waves in Thickness Measurements of Layers Deposited on Thin Plates

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***Abstract*—Layer thickness measurements using pseudo-Sezawa waves have been proposed, in which ultrasonic waves were obliquely applied to a layered surface of a specimen. A case in which the plate thickness of the specimen is so thin that it can not be regarded as a half space is studied. A number of modes of plate waves are then excited in addition to pseudo-Sezawa waves. The plate waves, giving rise to the appearance of extra dips in the power spectrum of reflected waves, cause difficulties in the measurements. To prevent the excitation of plate waves, it is proposed that a mask of a sound-insulating material having a slit aperture should be placed on the layered surface of the specimen. Experiments and theoretical calculations, using lead frames of LSI chips as typical test specimens with thin substrates, are made to demonstrate a performance of the present method in preventing the excitation of plate waves.**

## I. Introduction

An ACOUSTIC micrometer using pseudo-Sezawa waves has been developed and applied to thickness measurements of surface layers deposited on solid substrates [1]. In the acoustic micrometer pseudo-Sezawa waves were excited on a layered surface by ultrasonic waves obliquely applied through a propagating fluid (typically water). A dip was then observed in the power spectrum of a reflected wave at a specific frequency, at which pseudo-Sezawa waves were excited [2], [3].

When the thickness of a substrate is so thin that it cannot be regarded as a half space, the incident wave excites various modes of guided waves along the layered plate. Characteristics of the modes are discussed in detail by Farnell and Adler [16]. Throughout this paper, those modes are designated as "surface waves," which become asymptotic to surface waves on a layered half space as the frequency is increased. And other modes are designated as "plate waves." If the plate has no surface layer, the plate waves are known as Lamb waves [4]–[6]. Plate waves and Lamb waves have been studied for the purpose of nondestructive evaluation of materials. Typical examples are as follows: measurement of the plate thickness [7], estimation of the depth of planar cracks in ceramics by an acoustic microscope [8], observation of thin substrates with an acoustic microscope [9], [10], estimation of material properties of plates [11], investigation of images of multilayered materials [12], and estimation of elastic properties of composite materials [13]. In these studies plate waves and Lamb waves were intentionally employed for the measurement.

On the contrary, in layer thickness measurements by an acoustic micrometer using pseudo-Sezawa waves, the excitation of plate waves has caused an appearance of many extra dips, besides one caused by the excitation of pseudo-Sezawa waves, in the power spectrum of a reflected wave, and raised difficulties in measurements. This paper investigates the nature of the plate waves, and then proposes a method to circumvent the excitation of plate waves.

In Section II, experiments on layered plates and numerical calculations of reflection coefficients are made to study the nature of dips in the power spectrum. In Section III, a method to prevent the excitation of plate waves is proposed with a simple consideration based on a geometrical theory of acoustic propagation. An experiment using the method demonstrates its performance in preventing the excitation of plate waves. Then a diffraction theory of sound propagation is used to simulate the measurement by numerical calculations.

## II. Plate Waves and Surface Waves in Thin Plates

To investigate the nature of dips in the power spectrum, dispersion curves of the phase velocities for plate waves and surface waves in a layered thin plates are studied by experiments and numerical calculations.

### *A. Experimental Apparatus*

A block diagram of an acoustic micrometer [1] is shown in Fig. 1. An impulsive plane wave was applied to a layered surface of a specimen with a specific incident angle denoted by $\theta$ in Fig. 1. In a sensor unit used in this study, the incident angle $\theta$ was variable. The effective frequency range of piezoelectric transducers, which were made of ZnO films sputtered on transducer rods, was 20–130 MHz. Test specimens used in experiments consisted of

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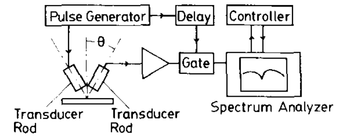


Fig. 1. Block diagram of acoustic micrometer.

42-alloy (42 percent Ni–Fe alloy) substrates with electroplate surface layers of gold. The plate thickness of the substrates was 225 μm, and the layer thickness ranged from 2 to 5 μm, reference values of which were measured by an X-ray fluorescence method [14]. A geometry of a test specimen and acoustic waves are schematically drawn in Fig. 2; the plate was immersed in water for the measurement.

### *B. Experiments on Layered Plates*

It was shown in the previous studies [1], [2] that the pseudo-Sezawa wave was most efficiently excited on a specimen consisting of a 42-alloy substrate and a gold layer when the incident angle $\theta$ was nearly equal to 27°. Therefore experiments were performed by changing $\theta$ from 18° to 41° with 1° steps, and at each incident angle, frequencies of dips in the power spectrum were measured.

Examples of measured spectra, at $\theta = 30°$, are shown in Fig. 3. The thickness of gold layers were 3.69, 3.49 and 3.31 μm for specimens in Figs. 3(a), (b), and (c), respectively. At a glance, it is inferred that there are two distinct kinds of dips in each spectrum: one kind is a series of roughly periodic dips with narrow width and shallow depth (denoted by ① in Fig. 3(c)), and the other kind is a rather wide and deep dip (emphasized with a dashed line and denoted by ② in Fig. 3(c)). In the vicinity of the dip ②, the two kinds of dips overlap each other making a complicated figure, therefore, the exact identification of the two kinds of dips is difficult. A rough estimation of center frequencies of dips ② in Figs. 3(a), (b), and (c) is listed in Table I, which indicates that $fd$ values (the product of dip frequency $f$ and layer thickness $d$) are approximately equal to an $fd$ value of a dip in case of a layered half space [1]; 210 MHz μm at $\theta = 30°$ for gold layers on 42-alloy substrates. This suggests that the dips ② were caused by the excitation of surface waves, which would become pseudo-Sezawa waves if the plate thickness were infinitely large.

From values of incident angles $\theta$ and dip frequencies $f$ measured for the test specimen with the layer thickness 3.31 μm, dispersion curves were obtained through

$$V = V_w / \sin \theta, \tag{1}$$

$$k = 2\pi f / V, \tag{2}$$

where $V_w$ is the sound velocity in water, and $V$ and $k$ are the phase velocity and wave number of plate waves, respectively. The values are plotted in Fig. 4.

### *C. Numerical Calculations*

Numerical calculations of a reflection coefficient $R(f, \theta)$ were performed for a plane ultrasonic wave incident on

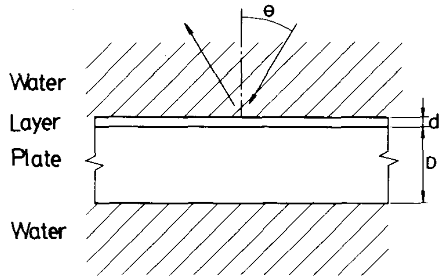


Fig. 2. Cross sectional view of layered plate immersed in water, irradiated with acoustic wave.

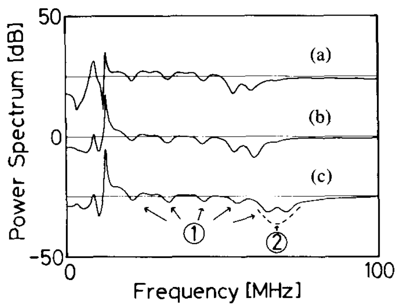


Fig. 3. Power spectra of waves reflected at gold layered 42-alloy plates. Plate thickness: 225 μm. Layer thickness: (a) 3.69 μm, (b) 3.49 μm, (c) 3.31 μm. Incident angle: 30°.

TABLE I
ESTIMATION OF FREQUENCIES OF DIPS ② IN FIG. 3[a]

| | Layer Thickness [μm] | Frequency of Dip ② [MHz] | [b]$fd$ [MHz · μm] | Deviation [percent] |
|---|---|---|---|---|
| (a) | 3.69 | 58 | 214 | +1.9 |
| (b) | 3.49 | 60 | 209 | −0.5 |
| (c) | 3.31 | 66 | 218 | +3.8 |

[a]Incident angle: 30°.
[b]$fd$ for layered half-space: 210 MHz · μm.

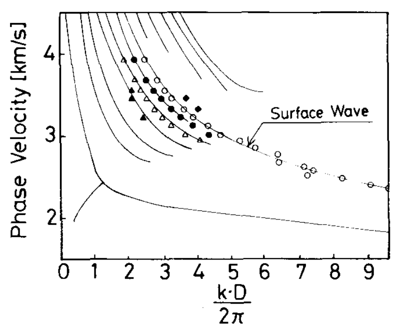


Fig. 4. Dispersion curves of phase velocities for waves excited in gold layered 42-alloy plate. Solid lines: theoretical. ○, ●, △, ▲, ♦: experimental. Layer thickness: 3.31 μm. Plate thickness: 225 μm.

TABLE II
MATERIAL CONSTANTS USED IN CALCULATIONS

| | Density [g/cm³] | $Vl$ [m/s] | $Vt$ [m/s] |
|---|---|---|---|
| Water | 1.00 | 1483 | — |
| Gold | 19.32 | 3240 | 1220 |
| 42-alloy | 8.10 | 4860 | 2600 |

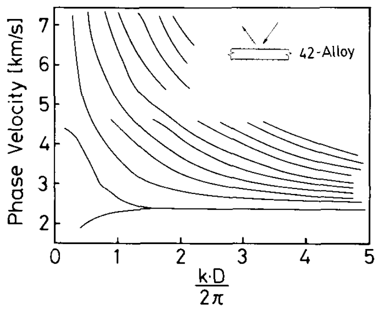


Fig. 5. Dispersion curves of phase velocities numerically calculated for waves in plate without surface layers.

a plate with a surface layer 3.31 $\mu$m thick, immersed in water. The calculations were made using a method described by Brekhovskikh [5], with the incident angle $\theta$ and frequency $f$ as parameters. Material constants used in the calculation are listed in Table II. Modulus of $R(f, \theta)$ exhibited a series of dips in the $f - \theta$ plane. From the loci of the dips in the $f - \theta$ plane, dispersion curves of the phase velocities were obtained by (1) and (2), and plotted in Fig. 4 with solid lines. An agreement is seen with experimental values.

The calculation was also carried out for a plate without a surface layer immersed in water, and dispersion curves of the phase velocities, thus obtained, are shown in Fig. 5. They are dispersion curves of leaky Lamb waves [5].

It can be seen in Fig. 4 that an additional mode, depicted as a surface wave in the figure, comes to be excited because of the deposition of a surface layer on the plate. As discussed in Section II-B, this surface wave becomes a pseudo-Sezawa wave when the plate thickness becomes infinite. Dispersion curves of other modes in Fig. 4, which we call plate waves, deviate from those of leaky Lamb waves when a surface layer is deposited.

## III. A METHOD TO PREVENT THE EXCITATION OF PLATE WAVES

From Fig. 3, one cannot readily define a simple and accurate technique to estimate the layer thickness from the power spectrum for a layered plate. In the following, we propose a method that can be easily implemented.

### *A. A Method Using a Mask with a Slit*

Fig. 6 schematically shows a cross sectional view of a thin plate with a layer on it. The thickness of the plate is

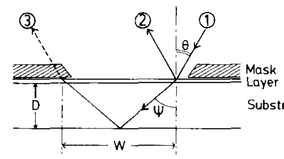


Fig. 6. Schematic description of sound-insulating mask with slit aperture placed on layered surface of plate.

$D$. An arrow ① represents an incident wave. The incident angle is $\theta$. An arrow ② represents a wave reflected at an upper surface, while an arrow ③ represents a wave reflected at a bottom surface of the plate. In the present case with $\theta \approx 30°$, the wave ③ propagating in the P late is a transverse wave. From the Snell's law,

$$\sin \theta / V_w = \sin \psi / V_t \tag{3}$$

where $V_t$ is the transverse sound velocity in the plate and $\psi$ is the refraction angle. The excitation of plate waves can approximately be regarded as a resonance of the waves ② and ③. The condition of the resonance is easily derived,

$$f_m = m \cdot V_t/(2D \cdot \cos \psi) \tag{4}$$

where $f_m$ is an $m$th resonant frequency, and $m$ is a nonnegative integer. The distance $W$ in Fig. 6 is subject to the condition,

$$W = 2D \cdot \tan \psi. \tag{5}$$

Thus it might be possible to prevent the excitation of plate waves by placing a sound-insulating mask having a slit aperture on the layered surface, as shown in Fig. 6. A typical material of the mask is silicon rubber. The width of the slit must be less than $W$ in (5). Physical phenomena belonging to the surface wave are essentially confined in the vicinity of the layered surface, therefore, the mask might not seriously affect the spectral components corresponding to the excitation of surface waves.

In order to evaluate the performance of this method, an experiment was made. The thickness of a surface layer of a test specimen was 3.72 $\mu$m, and the incident angle was 30°. The width of a slit in the mask was 1 mm. A comparison of two spectra obtained by measurements with and without the mask is shown in Fig. 7. It is obvious from the figures that, by using a mask, dips caused by plate waves can be removed and only a dip by the surface wave, which is essentially the pseudo-Sezawa wave, can be recovered.

### *B. A Simulation by a Diffraction Theory*

A diffraction theory of acoustic propagation [15] is given in the following to simulate an ultrasonic wave reflected at a masked surface of a layered plate.

Fig. 8 shows a coordinate system for the calculation. For the sake of simplicity, we treat it as a two-dimensional (2-D) problem. We suppose that a plane wave with frequency $f$ is propagated from plane 1 through water to-

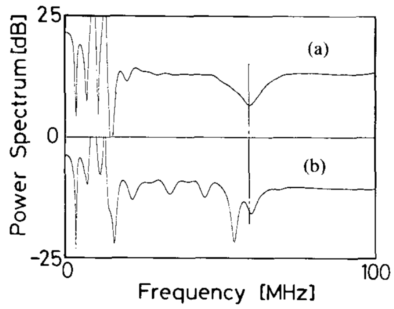


Fig. 7. Power spectra of waves reflected at gold-layered 42-alloy plate. (a) Measured with mask, and (b) without mask. Slit width of mask: 1 mm. Incident angle: 30°. Layer thickness: 3.72 μm. Plate thickness: 225 μm.

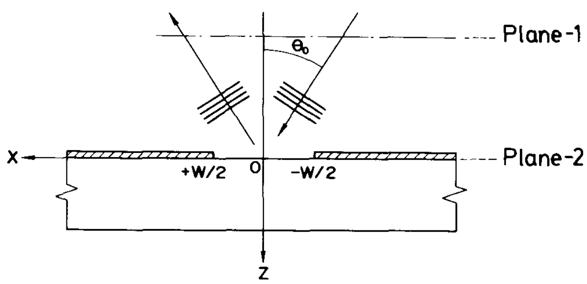


Fig. 8. Coordinate system used for calculations.

ward a layered surface of a thin plate. The incident angle is $\theta_0$. At plane 2 where $z = 0$, a potential function of the incident wave is,

$$\Psi(x) = \exp(i\xi_0 x) \tag{6}$$

where $\xi_0 = k \sin \theta_0$, and $k = 2\pi f / V_w$. Plane 2 is at the interface between water and a layered surface. Now let us suppose that a mask placed at plane 2 absorbs the incident wave in regions $|x| > W/2$, and leaves it intact in a region $-W/2 < x \leq +W/2$. Therefore the incident wave is modified to

$$\Psi(x) = \begin{cases} \exp(i\xi_0 x), & -W/2 < x < +W/2, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

The angular spectrum of the incident wave is then

$$\begin{aligned} \Phi(\xi) &= (1/2\pi) \int_{-W/2}^{+W/2} \exp(i\xi_0 x) \exp(-i\xi x)\, dx \\ &= \left(\sin\left((\xi - \xi_0)W/2\right)\right) / \left(\pi(\xi - \xi_0)\right). \end{aligned} \tag{8}$$

When the incident wave is reflected by the layered surface of a specimen, the angular spectrum of the reflected wave can be obtained by multiplying the right-hand side of (8) with a reflection coefficient $R(f, \theta)$ for the layered surface. The reflected wave is also inhibited to propagate backward through plane 2 at $|x| > W/2$, because of the presence of the mask. Therefore a potential function of the reflected wave at plane 2 just above the mask is

$$\Psi(x) = \begin{cases} \int \left(R(f, \theta) \cdot \sin\left((\xi - \xi_0)W/2\right) / \right. \\ \quad \left. \left(\pi(\xi - \xi_0)\right)\right) \exp(i\xi x)\, d\xi, \\ \qquad -W/2 < x < +W/2, \\ 0, \quad \text{otherwise,} \end{cases} \tag{9}$$

where the integral is taken from $-\infty$ to $+\infty$, and $\theta$ is a function of $\xi$ through

$$\sin \theta = \xi / k. \tag{10}$$

From (9), the angular spectrum of the reflected wave at plane 2 is finally obtained as

$$\begin{aligned} \Phi(\xi) = \int &\left(\sin\left((\xi - \xi')W/2\right) / \left(\pi(\xi - \xi')\right)\right) \\ &\cdot R(f, \theta') \cdot \left(\sin\left((\xi' - \xi_0)W/2\right) / \right. \\ &\left. \left(\pi(\xi' - \xi_0)\right)\right) d\xi' \end{aligned} \tag{11}$$

where $\xi' = k \sin \theta'$ and $\xi_0 = k \sin \theta_0$. Now we change variables from $\xi$, $\xi'$ and $\xi_0$ to $\theta$, $\theta'$ and $\theta_0$, respectively, and expand $\theta'$ around $\theta_0$, leaving only terms up to first order in $\gamma$:

$$\gamma \equiv (\theta' - \theta_0). \tag{12}$$

Then the angular spectrum of the reflected wave at a reflection angle $\theta$ equal to $\theta_0$ is approximated by

$$\begin{aligned} \Phi(\theta_0) \approx \int &\left(\sin\left(k\gamma(W/2)\cos\theta_0\right) / \left(\pi k \gamma \cos \theta_0\right)\right)^2 \\ &\cdot R(f, \theta_0 + \gamma)\, d\gamma, \end{aligned}$$

which is expected to be a main contribution to the receiver output in this study. The contour of integration lies in a complex $\gamma$ plane, but a major contribution to the integral comes from a region specified as

$$|\gamma| \leq \pi / (kW \cos \theta_0). \tag{14}$$

Equations (13) and (14) mean that the power spectrum of the reflected wave is a weighted average of the reflection coefficient over the restricted region of $\theta$ around the incident angle $\theta_0$.

Power spectra of reflected waves ($\log_{10} |\Phi(\theta_0)|^2$, strictly speaking) were numerically calculated according to (13) and (14). We assumed the slit width $W = 0.6$ mm in the calculation instead of 1 mm, because the actual mask used in the experiments had a finite thickness so that the slit width was effectively reduced for obliquely incident waves. Results obtained by assuming no mask and a mask are shown in Figs. 9(b) and (a), respectively. These two figures correspond to ones experimentally obtained and shown in Figs. 7(a) and (b). The two sets of figures show an excellent agreement.

Numerical calculations were also performed for specimens with different layer thickness. Dip frequencies obtained from the calculations are plotted in Fig. 10 with

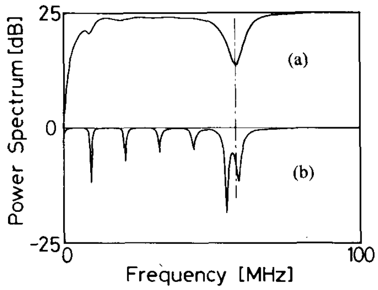


Fig. 9. Calculated power spectra of waves reflected at gold-layered 42-alloy plate, (a) with mask, and (b) without mask. Slit width of mask: 0.6 mm. Incident angle: 30°. Layer thickness: 3.72 μm, plate thickness: 225 μm.

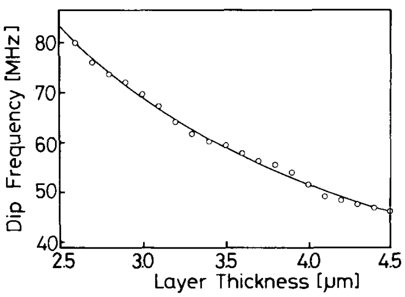


Fig. 10. Calculated dip frequency as function of layer thickness. Open circles are calculated for gold-layered 42-alloy plate, 225 μm in plate thickness, with mask, 0.6 mm in slit width. Solid line is calculated for layered half-space. Incident angle: 30°.

open circles as a function of the layer thickness $d$. A solid curve in Fig. 10 stands for dip frequencies that were calculated for a layered half space. This figure suggests that dip frequencies for a layered plate measured by the present method using a mask would be in good agreement with ones for a layered half space, although deviations of the plotted data from the solid line indicate that the effect of the plate waves was still not completely removed.

## IV. Conclusion

An acoustic micrometer using pseudo-Sezawa waves was applied to thin plates with surface layers for layer thickness measurements taking lead frames of LSI's as test specimens. When the plate was thin, a number of plate waves as well as surface waves were excited by obliquely incident ultrasonic waves. It was found that the layer thickness measurement became difficult when the plate waves were excited. In order to solve the difficulty, it was proposed that a mask with a slit aperture should be placed on the layered surface of the specimen to prevent the excitation of the plate waves. Experiments were made to confirm the validity of the method. Numerical calculations using a diffraction theory of sound propagation were also made, and spectra obtained by the simulation have shown an excellent agreement with experimental ones.


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## References


[1] Y. Tsukahara, N. Nakaso, J. Kushibiki, and N. Chubachi, "An instrument for layer thickness measurement using pseudo-Sezawa waves," in *Proc. IEEE Ultrason. Symp.*, 1986, pp. 1031–1035.

[2] Y. Tsukahara, E. Takeuchi, E. Hayashi, and Y. Tani, "A new method of measuring surface layer thickness using dips in angular dependence of reflection coefficients," in *Proc. IEEE Ultrason. Symp.*, 1984, pp. 992–996.

[3] E. Takeuchi, Y. Tsukahara, E. Hayashi, H. Masuda, and Y. Tani, "Application of reflection coefficient dip to layer thickness measurement by acoustic microscope," *Jpn. J. Appl. Phys.*, vol. 24, Suppl. 24-1, pp. 190–192, 1985.

[4] B. A. Auld, *Acoustic Fields and Waves in Solids.* New York: John Wiley, 1972, vol. 2, pp. 66–104.

[5] L. M. Brekhovskikh, *Waves in Layered Media.* New York: Academic Press, 1980, pp. 41–60.

[6] H. Lamb, "On waves in an elastic plate," *Proc. Roy. Soc. London*, Series A, vol. XCIII, p. 114, 1917.

[7] C. L. Frederick and D. C. Worlton, "Ultrasonic thickness measurements with Lamb waves," *Nondestruct. Test.*, vol. 20, pp. 51–55, 1962.

[8] K. Yamanaka, *Jpn. J. Appl. Phys.*, vol. 25, Suppl. 25-1, pp. 191–193, 1986.

[9] R. D. Weglein, "Metrology and imaging in the acoustic microscope," in *Scanned Image Microscopy*, E. A. Ash, Ed. London: Academic Press, 1980.

[10] J. Kushibiki and N. Chubachi, "Material characterization by line-focus-beam acoustic microscope," *IEEE Trans. Sonics Ultrason.*, vol. SU-32, no. 2, pp. 189–212, 1985.

[11] R. D. Weglein, S. E. Benson, and N. Vasudevan, "Lamb wave diagnostics with the acoustic microscope," in *Proc. IEEE Ultrason. Symp.*, 1985, pp. 763–767.

[12] T. Kund, A. K. Mal, and R. D. Weglein, "Calculation of the acoustic material signature of a layered solid," *J. Acoust. Soc. Am.*, vol. 77, no. 2, pp. 353–361, 1985.

[13] D. E. Chimenti and A. H. Nayfeh, "Leaky Lamb waves in fibrous composite laminates," *J. Appl. Phys.*, vol. 58, no. 12, pp. 4531–4538, 1985.

[14] H. H. Behncke, "Coating thickness measurement by the X-ray fluorescence method," *Metal Finishing*, vol. 82, no. 5, pp. 33–39, 1984.

[15] L. M. Brekhovskikh, *Waves in Layered Media.* New York: Academic Press, 1980, pp. 101–117.

[16] G. W. Farnell and E. L. Adler, "Elastic wave propagation in thin layers," Ch. 2, in *Physical Acoustics IX*, W. P. Mason and R. N. Thurston, Eds. New York: Academic Press, 1972, pp. 35–127.



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