TRANSMISSION SCANNING ACOUSTIC MICROSCOPY FOR

TILTED PLATE SPECIMENS*

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I. INTRODUCTION

In transmission scanning acoustic microscopy (SAM) [1,2,3] the plate-specimen under examination is usually aligned with its surface normal parallel to the lens axis in order to optimize the spatial resolution. However, we have found that in many instances a higher acoustic transmission and additional image contents can be facilitated by tilting the specimen such that its surface normal is at a small angle with respect to the lens axis (Fig. 1). For a small tilt angle, the image degradation due to reduced spatial resolution is insignificant with relatively small numerical aperture lenses. It is thus

![Fig. 1 Geometry of a 150 MHz Transmission SAM Used to Measure Angular Power Spectra of Plate Specimens](image)

*This work was supported in part by the MICRO Project of the University of California and the Industrial Matching Fund from Rockwell International.

+Presently with Industrial Electronics Group Technology Center, Hughes Aircraft Company.
desirable to study plate specimens under this particular mode of operation. It is to be noted that reflection scanning acoustic microscopy that utilizes oblique incidence of the acoustic wave has been reported [4]. In this paper, the basic mechanisms of these angle-dependent acoustic transmission and image contrasts are studied through an angular-spectrum technique [4-9]. The analysis to be presented shows that acoustic resonance, mode conversion and the numerical aperture of the confocal lenses are the dominant factors in determining the transmission contrast of a plate specimen. Application of this tilt-specimen mode of operation to acoustic imaging of isotropic and anisotropic materials is also addressed.

Acoustic resonance at normal incidence was recently utilized by us for characterization of defects in thick specimens using a 150 MHz transmission SAM [10]. For a collimated acoustic beam resonance occurs at several incidence angles that depend upon the specimen thickness [11]. For a thin specimen this resonance transmission may occur at an incidence angle which is greater than the shear-wave critical angle [11, 12].

For a focused acoustic beam as in SAM, the angle-dependent acoustic transmission as a function of the numerical aperture of the acoustic lens is analyzed.

Another dominant factor that affects the transmission angular spectrum concern mode conversion which refers to transfer of the incident longitudinal waves into the shear waves in the specimen. The calculated transmission angular spectrum in the presence of mode conversion is compared with that obtained without mode conversion. The relative contribution of each kind of wave to the image contrast is thus determined as a function of the incidence angle and the numerical aperture of the acoustic lenses.

II. THEORETICAL FORMULATION

This section presents an analysis for calculating the induced voltage at the receiving transducer as a function of the tilt angle of the specimen and other relevant parameters in a confocal transmission scanning acoustic microscope.

For a confocal transmission scanning acoustic microscope, with untitled specimen, Wickramasinghes' theory [8] can be applied to show that:

\[
V = \int P_0 (r) P_5 (r) U_0 (r) U_5 (r) T(K r / K) dr
\]

\[
= \int P_0 (r) P_5 (r) U_0 (r) U_5 (r) T(Sin \psi) dr
\]

\[ (1) \]

\[ V: \text{Transducer output voltage} \]

\[ r: \text{radial distance from the lens axis} \]

\[ P_0 (r), P_5 (r): \text{pupil functions of the transmitting and receiving lenses, respectively} \]
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\[ U_0(x,y), U_5(x,y); \] acoustic fields on the planes 0 and 5, respectively, in the absence of the specimen

K: wave vector of a Fourier (plane-wave) component of the focused acoustic beam

\[ K_r: \] the component of K on the focal plane

\[ K_r/K = r/f = \sin \psi \] [7]

\[ \psi: \] the angle between the lens axis and the propagation direction of a plane-wave component

f: focal length of the two identical confocal lenses

and

T: the acoustic transmission coefficient of the water-specimen-water system.

It is to be noted that measurement of T for an aluminum plate in water using transmission probes was previously reported. [13].

Now for a specimen tilted at an angle \( \theta \) as shown in Fig. 1, Eq. (1) is modified to yield:

\[ V(\sin \theta) = \frac{1}{2} \left\{ \int_0^\infty r P_0(r) P_5(r) U_0(r) U_5(r) [T(\sin \phi_1) + T(\sin \phi_2)] \right\} \, dr (2) \]

where \( \phi_1 = \theta + \sin^{-1}(r/f) \) and \( \phi_2 = \theta - \sin^{-1}(r/f) \). The reason for separating the transmission coefficient T into two parts is that one half of the cross section of the focused acoustic beam is incident on the specimen at angles \( \phi_1 \) where \( \theta \leq \phi_1 \leq \theta + \pi/2 \) (radian), while the other half is at angles \( \phi_2 \) where \( \theta - \pi/2 \leq \phi_2 \leq \theta \).

For a collimated acoustic beam incident on a lossy plate specimen which is immersed in a liquid, the transmission coefficient is given by [11]:

\[ T(\theta) = \frac{2N}{[2M + j(N^2 - M^2 + 1)]} \] (3)

where

\[ M = (Z_2/Z_1) \cos^2 \theta S \cot P + (Z_{2S}/Z_1) \sin^2 \theta S \cot Q \]
\[ N = (Z_2/Z_1) \cos^2 \theta S / \sin P + (Z_{2S}/Z_1) \sin^2 \theta S / \sin Q \]
\[ Z_1 = \rho_1 c_1 / \cos \theta, \quad Z_2 = \rho_2 c_L / \cos \theta_L, \quad Z_{2S} = \rho_2 c_S / \cos \theta_S \]
\[ P = K_L d \]
\[ Q = K_S d \]

and
$\rho_1, \rho_2$: Mass densities of water and the specimen, respectively

c_1: longitudinal wave velocity in water

c_L, c_S: longitudinal and shear wave velocities in specimen

$\Theta$: incidence angle (from water)

$\Theta_L, \Theta_S$: refraction angles in specimen for the longitudinal and shear waves

d: specimen thickness, and

$K_L, K_S$: complex wave vectors in thickness direction of the specimen for longitudinal and shear waves (imaginary part accounts for the acoustic attenuation coefficient).

By solving Eq. (3) as a function of the incidence angle $\Theta$, we can determine the angles at which resonance transmission occurs. Eq. (3) shows implicitly that the larger the specimen thickness, the higher the number of resonance transmission. However, as the specimen thickness increases the peaks of the resonance transmissions become weaker and are eventually reduced to a small value due to increased acoustic attenuations in the specimen. Such resonance transmission affects the transducer voltage not only through enhancement of acoustic transmission, but also through sharp phase changes (180°) in the transmitted plane-wave components such as the calculated example shown in Figure 2. As a result, when the specimen is tilted to one of the resonance angles in a transmission SAM, some of the incident acoustic Fourier components will incur sharp phase changes while others will not. As a result, destructive interference occurs among these two portions of the spherical wavefront. The degree of destructive interference is a sensitive function of local material composition (or elastic parameters) and irregularity in the front surface of the specimen. In other words, the

Fig. 2 Calculated Phase Changes in the Plane Acoustic Waves Transmitted Through an Aluminum Plate of 0.156 mm in Thickness (Frequency-Thickness Product = 2.34X10⁶ meter/second)
image contrast of the specimen should be enhanced accordingly. Experimental verification of this contrast enhancement is given in Section III. It should be noted that in reflection SAM such sharp phase changes also occur in the leaky Rayleigh wave radiated when an acoustic wave impinges upon a specimen at the Rayleigh wave critical angle [4].

Equations (2)-(4) form the basis for generation of the numerical solutions for the output voltage of the transmission SAM with a tilted specimen. The merit of the above formulation is that the product $P_0(\theta)P_0(\theta)U_0(\theta)U_0(\theta)$ in the integrand can be viewed as a generalized pupil function to include the effects of lens geometry, nonuniform acoustic field in the beam cross section, acoustic attenuation in water, and spherical aberration, etc. [9]. These effects are included in generating the numerical results to be given in Section III.

Finally, it should be noted that we have implicitly neglected the effect of the specimen thickness on the acoustic fields in Eq. (1).

In general, the acoustic fields on both sides of a plate specimen cannot be assumed to be the same without introducing some error. However, for the case involving confocal acoustic lenses of relatively small numerical aperture and long focal length such as the ones employed in this study, this error does not drastically affect the results. This observation is in agreement with the conclusion that for a specimen thickness less than the depth of field of the beam (or range resolution) plane-wave approximation results in only a small phase error in the transmitted acoustic beam [14].

III. NUMERICAL AND EXPERIMENTAL RESULTS

We have calculated the angular power spectra of plate specimens in a confocal transmission SAM at 150 MHz using Eq. (4)-(7). For example, Fig. 3(a) and 3(b) show the calculated results for an aluminum plate of 254 μm in thickness with the numerical aperture of the acoustic lenses as a parameter. It is seen that both the number and the intensity of the enhanced transmission angles decrease as the numerical aperture of the acoustic lenses is increased. This is accounted for by the fact that destructive interference among the Fourier components of varying propagation directions increases with the numerical aperture of the incident acoustic beam.

To verify the aforementioned theoretical predictions an experiment was carried out using an aluminum plate of the same thickness as that used in obtaining Fig. 3. The experimental setup as shown in Fig. 1 is the same as that employed in the conventional transmission SAM [1-3] except that a precision rotation jig with an accuracy of one-fourth of a degree is used to rotate the specimen plane relative to the focal plane. The numerical aperture of the acoustic lenses used for the experiment is 0.156. Figure 4 shows that angular spectra measured. By comparing Fig. 3(b) with Fig. 4, we see that the agreement between theory and experiment is quite satisfactory and the theory correctly predicts the incidence angle for maximum acoustic transmission, namely, $6.3^\circ$.

IV. CONTRAST ANALYSIS

It is also desirable to tilt the specimen by a small angle such that the angular contrast, which is defined as the slope of the angular
power spectrum \( \frac{dV}{d\varnothing} \), is a maximum. In other words, a small incident angle is searched to maximize the following expression:

\[
\frac{dV}{d\varnothing} = \cos\varnothing \frac{dV}{dsin\varnothing}
\]

\[
= \frac{1}{2} \cos\varnothing \int rP_0(r)P_5(r)U_0(r)U_5(r) \left[ \cos\phi_1 T'(\sin\phi_1) + \cos\phi_2 T'(\sin\phi_2) \right] dr
\]

where \( T'(\sin\phi_1) \) refers to differentiating \( T(\sin\phi_1) \) with respect to its argument. Note that \( dV/d\varnothing \) is approximately equal to \( dV/dsin\varnothing \) for a small tilt angle \( \varnothing \) for the specimen. Near the angle of maximum angular contrast any small variation in the incidence angle due to local roughness or curvature in the surface of the specimen would result in a large variation in the transmitted acoustic power. In other words, the angular contrast constitutes an important contrast mechanism in the transmission SAM. From Eq. (5), we see that it is a function of the lens pupil function, and the orientation plus the acoustic parameters of the specimen. An appropriate incident angle for the aluminum specimen studied was found to be \( 5^\circ \leq 6^\circ \) as can be seen from Fig. 4.

Acoustic transmission images of the same aluminum plate as described in Section III, but with lossy adhesive layer residing on a great portion of the surface of the plate, were used to verify this observation. The adhesive layer was of the commercial product Loctite 420 and was approximately 0.5 mil thick. Figures 5 (a)-(c) show the image obtained. It should be mentioned that the boundary of the adhesive layer (partly shown) coincides with that of the dark area in Fig. 5. By first comparing the bright areas in these images, we see that the acoustic transmission is considerably higher at the incidence angle of \( 5^\circ \leq 6^\circ \). Furthermore, additional image contents are seen in the portion of the image that corresponds to the adhesive area. Thus, it confirms the prediction that by examining the specimen at both normal incidence and oblique incidence of suitable angle a higher degree of image detail can be achieved.
The theoretical study presented thus far can be extended to treat an anisotropic specimen. Since the acoustic transmission coefficient for anisotropic materials depend on not only the tilt angle but also the orientation of the specimen surface with respect to the crystal axis, the enhanced image contrast discussed above should be even more readily observed.

We have seen in Figs. 3(a) and 3(b) that acoustic resonance greatly affects the transmission angular spectra and image contrast. Let us now examine the case in which acoustic resonance is unimportant in the angular range of concern such as an aluminum membrane of 3 microns in thickness. The calculated angular spectra based on Eq. (2) show that the normalized transducer voltage is 0.37, independent of the incident angle for both collimated beam and focused beam, with the latter being formed by the acoustic lens with a numerical aperture equal to 0.156. This suggests that there exists little angular image contrast when acoustic resonance is insignificant because dV/dθ is near zero. In a related study on image contrast with thin aluminum specimens (one-quarter to one acoustic wavelength in thickness) [15], we have however experimentally observed that the transmission image contrast was drastically altered if the numerical aperture of the acoustic lens is large enough.
to excite a leaky lamb wave. It should be noted that in this situation the model that includes only longitudinal and shear waves would not be adequate.

We shall now point out a major difference between transmission and reflection SAM's in terms of contrast mechanisms. First, we recall that in the conventional reflection SAM the transducer voltage [7] is given as follows:

$$V(Z) = \int_0^\infty r[U_0(r)]^2 P_0(r)P'_0(r)R(r/f) \exp[-j(K_0Z/f^2)r^2]dr$$ (6)

where $Z$ refers to the location of the front surface of the specimen along the lens axis with the acoustic focus located at the origin of the coordinate system. Any nonuniformity or roughness on the specimen surface will correspond to variation in the $Z$ value, and therefore $V(Z)$. The image contrast as a result of such variation in $V(Z)$ can be defined as the axial contrast or $Z$-contrast and mathematically given as follows:

$$\frac{dV(Z)}{dZ} = \int_0^\infty r[U_0(r)]^2 P_0(r)P'_0(r)R(r/f) \left\{ \exp[-j(K_0Z/f^2)r^2] \right\} \left( -j \frac{K_0r^2}{f^2} \right) dr$$ (7)

Secondly, due to excitation of leaky Rayleigh waves, contrast reversal may also occur as the specimen is translated along the lens axis [3,16]. However, in the transmission SAM the $Z$-contrast as defined above is often insignificant because there is no dependence on $Z$ in Eq. (1). Rather, the primary variation in the image as the specimen is translated along the lens axis is due to the defocusing effect. Our measurements with acoustically thick specimens (thickness of many acoustic wavelengths) also support this observation. Consequently, we may conclude that the angular contrast ($dV/d\theta$) due to acoustic resonance constitutes the dominant mechanism for material signature in a transmission SAM for acoustically thick specimens. We have also found experimentally that contrary to thick specimens both the angular contrast and the axial contrast are important in transmission SAM for thin specimens with a thickness in the order of one acoustic wavelength or smaller [15]. In this case it is believed that the axial contrast is caused by the interference between the transmitted longitudinal wave and the leaky Lamb wave [11]. The strength of the longitudinal wave is represented by the factor $T(\sin\psi)$ in Eq. (1).

There is one interesting problem concerning the role that shear wave plays in acoustic imaging using the transmission SAM [17]. The shear wave in the specimen is generated from the obliquely incident longitudinal wave through mode conversion, and the strength of the shear wave generated increases with the incident angle.

The transmission angular spectra for the same aluminum specimen as described in Section III with and without mode conversion were calculated using Eq. (2), and shown in Fig. 6(a) and Fig. 6(b), respectively. The latter case was obtained simply by letting $c_s$ in Eq. (4) equal zero. The resultant acoustic transmission coefficient is as follows:

$$T_0^{(0)} = \frac{2Z_1Z_2}{2Z_1Z_2 \cos \psi + j(Z_1^2 + Z_2^2) \sin \psi}$$ (8)
We have studied both theoretically and experimentally the transmission angular spectra and the image contrast of a tilted plate specimen using transmission scanning acoustic microscope. The transmitted acoustic power and the intrinsic image contrast as a function of the tilt angle of the specimen are studied in detail. Detailed study on an aluminum plate specimen was carried out using a 150 MHz transmission SAM that employs confocal lenses of relatively small numerical aperture and long focal length. A good agreement between
the theoretical predictions and the experimental results has been obtained. It is concluded that the angular contrast which originates from acoustic resonance and mode conversion constitutes the dominant contrast mechanism in a transmission SAM for acoustically thick specimens. Specifically, by orienting the specimen to a small tilt angle significant enhancement in transmitted acoustic power and/or angular image contrast due to acoustic resonance can be achieved with only slight degradation in spatial resolution. It is also found that, for a small tilt angle, the effect of mode conversion on the acoustic transmission and the image contrast is negligible for a SAM that utilizes relatively small numerical aperture lenses. The analytical results presented should be applicable to a transmission SAM operating at frequencies higher than 150 MHz.

REFERENCES