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AMPLITUDE AND PHASE ACOUSTIC MICROSCOPY
AND ITS APPLICATION TO QNDE

by

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AMPLITUDE AND PHASE ACOUSTIC MICROSCOPY

AND ITS APPLICATION TO QNDE

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INTRODUCTION

We have two amplitude and phase measuring acoustic microscopes, one at low frequency (3-10 MHz) which is used for measurements in metals and composites, and the other operating at frequencies of up to 200 MHz which is used for higher resolution measurements. The added dimension of having phase information allows us to use image processing for a variety of applications. We have demonstrated the following applications with these two microscopes: $V(z)$ inversion for reflectance function calculations, depth determination for delaminations in composite materials, slowness curve measurements in anisotropic materials, image enhancement of subsurface defects, measurements of depth of trenches in aluminum samples (scaled problem of silicon trenches), and measurement of visco-elastic properties of thin surfactant films on a water surface.

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Acoustic microscopy has become a major nondestructive evaluation tool for imaging, characterizing, and detecting defects in structural materials. The literature and this conference contain ample evidence of this fact. Except for our work at Stanford University, amplitude-only acoustic microscopes are used. We believe that the added image of phase variation across a sample gives a major advantage in image interpretation, signal processing, and material characterization. Thus, we have developed two acoustic microscopes that measure amplitude and phase, and that operate in the frequency range of 1-200 MHz.

The following is a list of problems that we have, over the last few years, solved by using amplitude and phase acoustic microscopy: (1) $V(z)$ inversion for reflectance function evaluation [1,2]; (2) thin film thickness measurements with a resolution corresponding to 0.1 degree phase detection sensitivity; (3) surface wave velocity variations due to anisotropy, surface residual stress, and thin film loading of a half space; (4) thickness determination of thick films such as delamination in composite materials [3]; (5) contrast enhancement by spatial filtering which is superior to the same process using amplitude-only information [4]; (6) surface roughness removal to image subsurface defects, such as imaging the back side of a coin through the front surface roughness at 10 MHz for a U.S. quarter and without time gating the back surface echo; (7) depth resolution enhancement by two-dimensional spatial deconvolution; and (8) measurement of the surface viscosity of thin films on the surface of the ocean [5].

Several parts of the above-mentioned work have been published; we will concentrate in this paper on the last two examples mentioned above.

A schematic diagram of the electronic set-up for amplitude and phase measurement with the low-frequency acoustic microscope is shown in Fig. 1. The major feature in this measurement scheme is the use of the divide by n and $n + 1$ chip, which allows us to step the phase of the signal by $360/n$ degrees at a time with respect to a fixed-phase reference. Thus, we use n mixings to determine the amplitude and phase of the signal at a point in the scanning field. This type of measurement enhances the accuracy and the sensitivity of the measurement by removing electronic offsets in the various components of the system. The high-frequency measurement, shown in Fig. 2, is essentially the same, except that due to the unavailability of very high-frequency divide-by chips, we mix the phase-shifted signal with a local oscillator to arrive at the frequency of operation. The mechanical scanning, display, and computer control of the microscope is conventional and merits no further mention in this paper.

Fig. 1. Schematic diagram of amplitude and phase low-frequency acoustic microscope.

THREE-DIMENSIONAL RESOLUTION ENHANCEMENT

For objects embedded in a uniform medium, the image formed as the microscope scans in all three dimensions is a convolution of the object with the microscope's three-dimensional impulse response.

$$g(\vec{x}) = h(\vec{x}) * * * f(\vec{x}) \quad (1)$$

where g is the image, h is the microscope's impulse response, and f is the object. In general the transducer's impulse response is less than ideal; it may have a broad central lobe or relatively large sidelobes. Figure 3a shows the line spread function of an F2 transducer operating at 3 MHz. This was experimentally determined by scanning a

Fig. 2. Schematic diagram of amplitude and phase high-frequency acoustic microscope.

(a)

(b)

Fig. 3. (a) Two-dimensional line spread function of F2 transducer. (b) Enhanced line spread function of same transducer.

(a)

(b)

Fig. 4. (a) Spatial frequency response of F2 transducer. (b) Enhanced spatial frequency response of same transducer.

200 μm wire. Notice the large diagonal sidelobes and that the width of the main lobe in the z direction is greater than 27 mm. The non-ideal characteristics of the microscope's impulse response degrade the quality of the acoustic images.

If a transducer can be characterized, there is a simple technique for numerically enhancing the effective transducer response of an acoustic microscope. It is possible to numerically tailor the transducer's effective impulse response to have a narrower central lobe, giving better resolution, or giving it smaller sidelobes.

First, we Fourier transform the images into the spatial frequency domain to get the image spectrum:

$$G(\vec{k}) = H(\vec{k})F(\vec{k}) \quad (2)$$

where G is the Fourier transform of g , H is the transform of h , and F is the transform of f . H is called the spatial frequency response (SFR) of the microscope.

$$G(\vec{k}) = \mathfrak{F}\{g(\vec{x})\} \quad (3)$$

This relationship can be inverted via an inverse Fourier transform.

$$g(\vec{k}) = \mathfrak{F}^{-1}\{G(\vec{x})\} \quad (4)$$

An image spectrum corresponding to a desired SFR is given by:

$$G_{Opt}(\vec{k}) = H_{Opt}(\vec{k})F(\vec{k}) \quad (5)$$

The desired image spectrum is obtained from the measured image by dividing Eq. (5) by Eq. (2) and cancelling terms:

$$G_{Opt}(\vec{k}) = \frac{H_{Opt}(\vec{k})}{H(\vec{k})} G(\vec{k}) \quad (6)$$

The enhanced image is obtained by inverse Fourier transforming G_{Opt} into the space domain. This amounts to convolving the experimental image with an "enhancing" filter whose spectrum is H_{Opt}/H .

Figure 4a shows the SFR of our transducer. Notice that it is non-zero only for a finite region in the spatial frequency domain. Therefore, Eq (6) is only valid in that range. This range is called the base of support for the SFR. In order for Eq. (6) to be valid, the base of support for H_{Opt} must be a subset of the base of support for H .

Figure 4b shows the enhanced SFR that was chosen. The base of support is an ellipse where the enhanced SFR is constant in amplitude and phase except the edge has a cosine squared taper.

Figure 3b shows the enhanced line spread function. Notice that the diagonal side-lobes have been eliminated and the width of the main lobe in the z-direction has been greatly decreased. The transverse resolution has been increased noticeably, but the depth resolution has been doubled, as shown in Fig. 5.

Fig. 5. (a) Line spread function of F2 transducer in x-direction. (b) Line spread function of F2 transducer in z-direction.

This dramatic increase in the z-direction can be better understood by looking in the spatial frequency domain. Figure 6 shows that the spectrum falls off rapidly as k_z differs from k , but that the spectrum is still well above the noise floor. Thus, the effective width of the useful spectrum can be numerically doubled.

EXPERIMENT: DEEP TRENCHES IN ALUMINUM

We applied this technique to measuring the profile of a deep trench (2 mm wide by 5 mm deep) using the F2 transducer. The sample is shown schematically in Fig. 7.

Fig. 6. SFR in kz direction of F2 transducer.

Fig. 7. Schematic of trench in Al.

The trench was designed to simulate a vertical capacitor in an integrated circuit ($2.5\ \mu\text{m}$ wide by $6\ \mu\text{m}$ deep). This technique could be scaled up in frequency to characterize integrated circuits with an optical microscope that measures amplitude and phase, or with an acoustic microscope operating at 2.5 GHz.

Figure 8 shows the original acoustic image compared to the enhanced image. The enhanced image qualitatively looks much sharper, showing the location of the bottom of the trench much more clearly. Comparing line scans in Figure 9 shows that the quantitative improvement has been dramatic. The transverse profile of the trench, when focused on the bottom, has been improved noticeably. The most dramatic improvement is

Fig. 8. X-Z plane image of trench in Al.

Fig. 9. (a) Original and enhanced line scans of trench in Al at $Z=0$.
 (b) Original and enhanced line scans of trench in Al at $Z=-5$ mm
 (c) Line scan through Al trench at $x=0$.

viscosity=1.053e-6 m/s
 surface tension=73 mN/m
 gravitational acceleration=9.83 m/s²

Fig. 10. Transient capillary wave evolution of a Gaussian dimple.

shown in the depth scan of the bottom of the trench. In the original image, the peak corresponding to the bottom occurs at $z = -7$ mm and there is another peak corresponding to the top surface. The enhanced image locates the bottom closer to the correct location at $z = -5$ mm with little interference from the top surface.

MEASUREMENT OF SURFACE TENSION

The ability of the acoustic microscope to measure phase allows us a novel application for acoustic microscopes, that is the measurement of ripples or capillary waves on the surface of water. Capillary waves are short-wavelength ripples on the surface of water which occur due to wind interaction with the water. Capillary waves are controlled by surface tension which acts to restore the disturbed surface of the water to its original position. We use the acoustic microscope to measure a controlled capillary wave packet that we excite with an acoustic transducer.

The schematic of the set-up is shown in Ref. 17. The first transducer excites a high-amplitude ultrasonic wave whose radiation pressure lifts the surface of the water and evolves as a transient capillary wave with a broad frequency spectrum. The second ultrasonic transducer which makes part of the phase measuring acoustic microscope is used to measure the amplitude of the capillary wave. The measured waveform is then analyzed to yield the surface tension of the water. This method allows us to measure the effect of surfactants on wind-wave interactions.

Figure 10 shows the result of a theoretical calculation of the capillary wave packet due to single Gaussian excitation 500 microns wide. The packet is measured at a distance of 4 cms from the source, and the surface tension of the water is taken to be

73/m ; surface viscosity is taken to be $1.053 \mu\text{m/s}$. The results of measurements on sea water samples agree very well with the theory of Fig. 10 and demonstrate the variation of the surface tension as a function of time, which is due to the rise of surfactants to the surface. The results indicate that we are indeed capable of measuring the properties of surface films on water.

CONCLUSIONS

Amplitude and phase measuring acoustic microscopes offer a major advantage in applying the microscope to material characterization problems. We demonstrated the improvement in most areas of application of acoustic microscopes with the added advantage of phase measurement. We also show a technique for making the phase measurement that is fairly simple, reliable, and which does not reduce the speed of operation of the instrument.

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