

PRECISION MEASUREMENT OF RAYLEIGH WAVE VELOCITY PERTURBATION

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INTRODUCTION

We have developed a technique for imaging variation in the surface characteristics of a sample by measuring the local perturbation of the Rayleigh wave velocity. A 50 MHz acoustic microscope operated out-of-focus is excited with a very short tone burst so that the on-axis longitudinal and off-axis Rayleigh reflection pulses are temporally separated. The relative phase between these two signals is measured using a synchronous detection scheme. This technique has a potential sensitivity of 10 ppm. We have demonstrated experimentally that we can detect a 240 Å thick film of indium deposited on glass which corresponds to a velocity perturbation of 0.18%.

A very important application of acoustic microscopy is materials characterization. The general approach is based on the variation in contrast as the distance between the acoustic microscope and the specimen is changed, the so-called acoustic material signature or $V(z)$ effect.¹⁻⁴ The contrast mechanism is well understood in terms of the interaction between the acoustic properties of the reflecting surface and the angular spectrum of the focused beam.⁴ Figure 1 depicts the corresponding ray model. The surface of the substrate is located above the focal plane of the acoustic lens. For materials with Rayleigh velocities higher than that of water, the only significant contributions to the electrical output of the piezoelectric transducer are the on-axis ray and the outer rays which impinge on the water-solid interface at the Rayleigh angle and excite a leaky surface wave which re-radiates back to the acoustic lens. Since the two contributions are picked up on the same electrical channel, they interfere to give rise to periodic maxima and minima in the

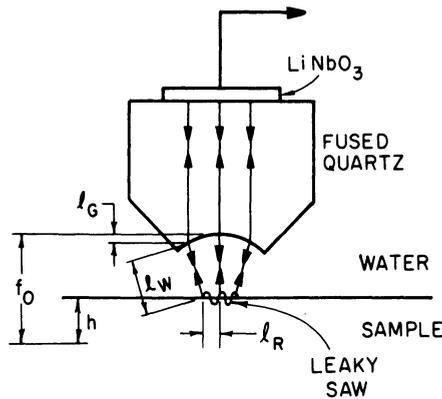


Fig. 1. Ray model showing the two significant contributions to the electrical output of an acoustic microscope: an on-axis ray which reflects normally from the sample surface and an outer ray which excites leaky surface waves at the water-solid interface.

$V(z)$ curve as the distance between the acoustic lens and the substrate is changed. The periodicity is characteristic of the material under examination. As a matter of fact, one can measure the interval Δz between two neighboring minima and use the equation

$$V_R = \left[\frac{V_W}{1 - 1 - \frac{V_W^2}{2f\Delta z}} \right]^{1/2}, \quad (1)$$

where V_W is the velocity in water and f is the frequency of operation, to determine the Rayleigh wave velocity V_R of the surface material. This measurement technique is not very precise, however, because in practice the locations of the minima are not sharply defined due to the presence of noise.

The measurement technique we have developed can directly and precisely determine small changes in the Rayleigh wave velocity over a surface. It is based on the consideration that the difference in propagation times ΔT for the on-axis ray path (L) and the Rayleigh wave ray path (R) can be substantial if the amount of defocusing h

is large, i.e., $h/f > 0.1$.

$$T_L = \frac{2(f_0 - h)}{V_W}$$

$$T_R = 2 \left(\frac{\ell_G}{V_G} + \frac{\ell_W}{V_W} + \frac{\ell_R}{V_R} \right)$$

$$\Delta T = T_R - T_L$$

where

$$\ell_G = r_0 (1 - \cos \theta_i) \quad \text{buffer rod path}$$

$$\ell_W = \frac{f_0 - h - \ell_G}{\cos \theta_R} \quad \text{water path}$$

$$\ell_R = r_0 \sin \theta_i - \ell_W \sin \theta_R \quad \text{Rayleigh path}$$

$$\sin \theta_i = \left[\frac{\sin \theta_R}{1 + \left(\frac{V_W}{V_G} \right)^2 - \frac{2V_W}{V_G} \cos \theta_R} \right]^{1/2}$$

$$\sin \theta_R = \frac{V_W}{V_R} \quad \text{Rayleigh angle}$$

$$f_0 = \frac{r_0}{1 - \frac{V_W}{V_G}} \quad \text{focal length}$$

and V_G is the velocity in the buffer rod and r_0 is the radius of curvature of the lens.

We have demonstrated for the first time that when a broadband transducer is excited with a sufficiently short duration pulse, the signals from the two ray paths can be separated temporally. Since the signal pulses are distinct one can, in principle, measure the time difference, or correspondingly the phase, between them. The relative phase so obtained is closely associated with the Rayleigh wave velocity of the sample. In our application, the objective is to measure velocity perturbation; therefore, the quantity of interest is the change in relative phase $\Delta\phi$ which is related to the Rayleigh wave velocity perturbation by

$$\begin{aligned}
 \Delta\phi &= 2\omega \left(\frac{1}{V_G} \frac{d\ell_G}{dV_R} + \frac{1}{V_W} \frac{d\ell_W}{dV_R} + \frac{1}{V_R} \frac{d\ell_R}{dV_R} - \frac{\ell_R}{V_R^2} \right) \Delta V_R \\
 &= -2\omega \frac{\ell_R}{V_W} \frac{\Delta V_R}{V_R} \\
 &= -2\omega \frac{h \tan \theta_R}{V_R} \frac{\Delta V_R}{V_R}
 \end{aligned} \tag{3}$$

The sum of the first three terms inside the brackets is identically zero. It corresponds to the first derivative of the total transit time through the lens, buffer rod, water, and sample surface. Based on Fermat's Principle, the total transit time is an extremum; therefore, the first derivative should vanish identically.

To carry out very sensitive phase measurements, we have constructed a 50 MHz reflection acoustic microscope specially designed for precision differential phase imaging. The system (Fig. 2) consists of two basic components: a mechanically-scanned acoustic microscope and a precision synchronous phase detector. The acoustic microscope consists of a 50 MHz lithium niobate transducer bonded to a fused quartz buffer rod. The radius of curvature of the spherical lens, ground in the front face of the quartz rod, is 3.175 mm, resulting in a focal length of 4.25 mm in water. The lens, with a radius of 3 mm, is fully illuminated by the transducer and thus produces a wide enough cone of insonification ($F 0.71$) to accommodate materials with surface velocities greater than 2.2 km/s. The specimen under inspection is typically positioned 1-2 mm above the focal plane to provide enough temporal separation between the on-axis longitudinal and the Rayleigh path reflections. Figure 3 shows an oscilloscope trace of the two signals when the transducer is excited with a three-cycle 50 MHz tone burst. The separation between the pulses is about 200 μ sec.

The synchronous phase detector consists of a single sideband generator which generates a 50 MHz cw signal and a synchronous 49.9 Mhz reference. The 50 MHz signal is gated to give a three-cycle tone burst which is used to drive the transducer. The longitudinal and Rayleigh wave path return echoes from the sample are then separated physically by means of a power splitter and time gating. Each of them is mixed with the 49.9 MHz reference to create a frequency spectrum centered on 100 kHz. The signals are passed through crystal filters to select the 100 kHz component, which is then fed into a lock-in amplifier for phase comparison. Due to delay in the acoustic path and the necessity to suppress extraneous echoes in the transducer, the repetition rate of the system is limited to about 30 kHz.

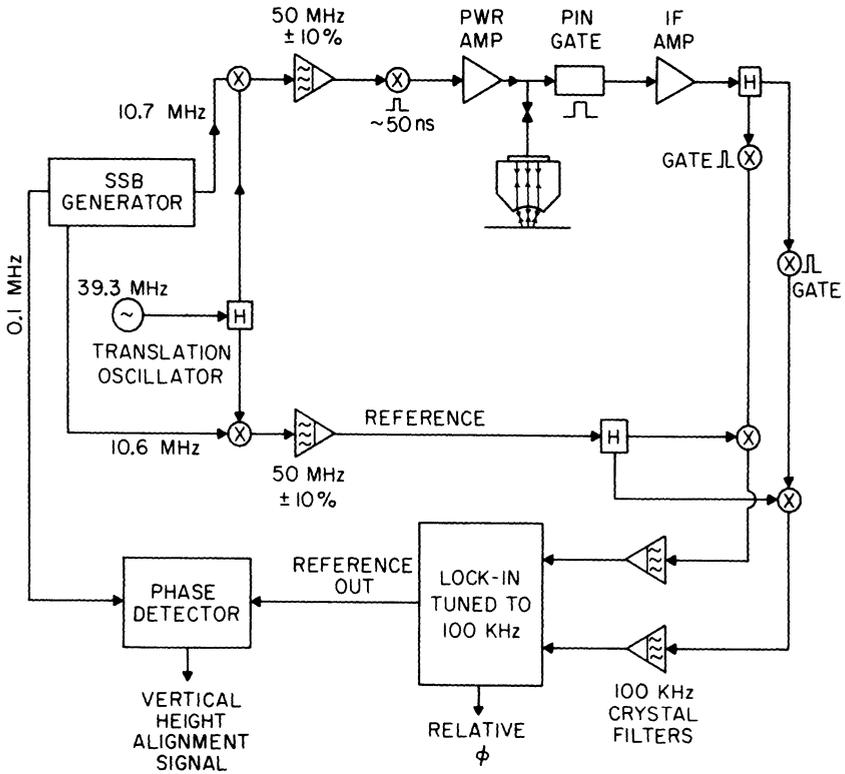
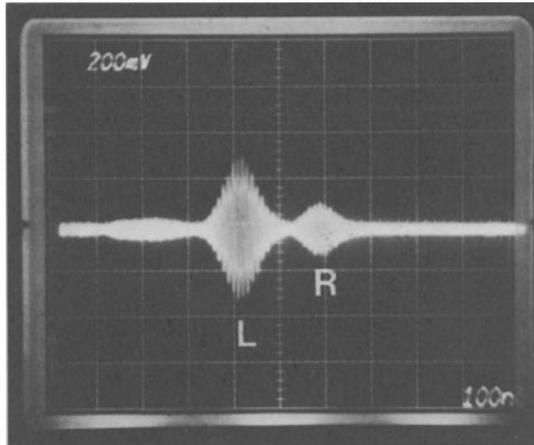


Fig. 2. Synchronous phase detection scheme for precision phase measurement.



EXCITATION: 3-CYCLE 50 MHz TONE BURST

Fig. 3. An oscilloscope tracing showing the temporally-separated on-axis reflection signal (L) and the Rayleigh wave path signal (R). The time separation between the two is about 200 μ sec.

This limitation represents a very low-duty cycle for a sampling 100 kHz sine wave, resulting in significant levels of phase noise. To enhance the signal-to-noise ratio, the lock-in amplifier is set to an integration time constant of 300 msec, thus imposing a limit on the maximum scanning speed of the acoustic microscope when a high degree of phase accuracy is required.

It is evident from Eq. (3) that the phase is also related to the distance between the lens and the specimen or, equivalently, h . This distance h is extremely sensitive to temperature variations in the mounting structure for the acoustic transducer. To eliminate the effects of thermal drift, a feedback control mechanism is incorporated in the system to maintain a constant distance between the lens and the sample. The compensation is accomplished by comparing the phase of the on-axis longitudinal reflection against a synchronous electronic, and therefore temperature stable, reference. The position of the transducer is continuously adjusted to keep a constant phase relationship between the acoustic and electronic signals. This feature has the added advantage of being able to track the surface topography of the sample; hence, the phase information obtained by this measurement technique is truly related to only the material properties of the surface.

A simple experiment was carried out to demonstrate the principle of the measurement technique, and also to obtain an appraisal of the capabilities of the measurement system. The test object is a multiple-thickness indium film deposited on glass. The thicknesses

are 240 Å and 620 Å, respectively. The thin indium film overlay causes a perturbation of the Rayleigh wave velocity on the glass substrate to be measured. Figure 4 shows a line scan over the surface of the test object obtained with the measurement system. The line scan exhibits a phase change of 7° for the 240 Å step change from glass to indium and another 11° for the 380 Å step change in indium thickness. It can be calculated to first order⁵ that the velocity perturbation on glass due to the indium overlay is about 0.18% for the 240 Å layer and 0.46% for the 620 Å layer. The spatial resolution of the system is determined from the transition width of the steps in the line scan to be about 1 mm, which gives a rough estimate of the length of the Rayleigh wave path along the water-solid interface.

Based on this estimate and the theoretically derived velocity perturbation, one would expect changes of 9.5° and 15° for the 240 Å and 380 Å step transitions, respectively. The experimentally measured results are somewhat lower than the calculated phase changes, but the two sets of results are consistent in that the percentage difference between them is the same for the two-step changes in thickness. The discrepancy is due to the uncertainty in the estimation of the Rayleigh wave path length. Also, the time separation between the on-axis reflection signal and the Rayleigh wave path signal pulses may not be sufficient, thus resulting in some residual interference between the two. It should also be noted that in the line scan, the small phase variation in the supposedly flat regions of the indium film are real and repeatable. The phase fluctuations are less than 0.5%, and are due to nonuniformity in the thickness of the indium film.

The sensitivity of the phase measurement is essentially limited by the lock-in amplifier to 0.1°. Thus, this technique has a potential sensitivity on the order of 1 part in 10⁵ change in velocity. In this experiment, a spherical lens is used to scan an isotropic test object with three different uniform regions. The phase reading registered is an average over a circular region about 1 mm in diameter, the spatial resolution of the system.

This phase measurement technique is a precise and direct means of mapping velocity perturbation on a surface, as compared to the usual procedure of measuring the interval between nulls of the $V(z)$ curve. If one should be interested in the absolute Rayleigh velocity, a careful $V(z)$ measurement could always be carried out at some reference position on the sample and the differential phase measurement would yield the velocity distribution of the surface.

The measurement system, with a spatial resolution of 1 mm in the present configuration, is adequately suited for macroscopic imaging. However, better spatial resolution is required to examine microscopic material structure. We are presently working on several ways to improve the spatial resolution of the system. The basic

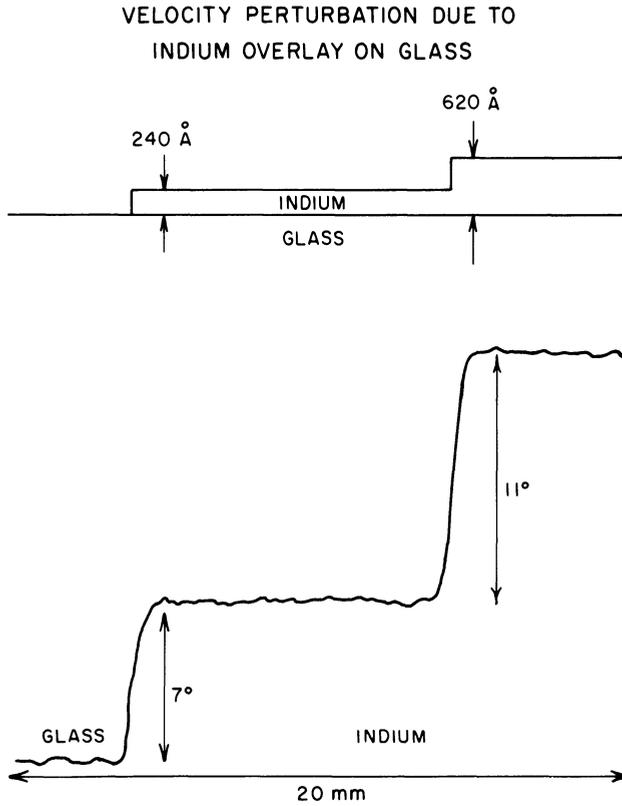


Fig. 4. Line scan of a multiple thickness indium film deposited on glass.

problem with the present system is that in order to achieve better spatial definition, the sample surface has to be located closer to the focus of the lens, resulting in a corresponding reduction in the time separation between the on-axis reflection and the Rayleigh

path signal pulses. Hence, the pulses tend to overlap in time, and since they are picked up on the same electrical channel, it becomes impossible to separate them physically to make precise phase measurements. We are engaged in designing and constructing transducers with two electrodes to process separately the two signals of interest. A small center electrode is used just for the on-axis reflection signal and a concentric ring electrode is used exclusively for the Rayleigh path signal. Since the signals are physically separated to begin with, time overlap is no longer a problem. Consequently, the sample can be moved closer to the focal plane of the lens to achieve better spatial resolution by shortening the Rayleigh wave path on the surface of the substrate. The penalty, of course, is a loss in phase resolution because of the shorter Rayleigh path. Nevertheless, in many practical applications, where a high degree of phase accuracy is not needed, the large reserve of phase sensitivity inherent in the measurement system can be traded for spatial resolution. There are other interesting possibilities with this electrode configuration. The ring electrode can be segmented into diametrically opposite pairs which can be multiplexed to launch a Rayleigh wave in different directions for measuring anisotropy in different materials. Another obvious way of improving the spatial resolution of the system is to use higher frequency transducers with the same percentage bandwidth. Since the impulse response is more compact in time, the sample can be located closer to the focal plane to better the spatial resolution while still maintaining adequate time separation between the pulses of interest. There is no loss in phase sensitivity because, at a higher frequency of operation, the same number of acoustic wavelengths is compressed into a shorter Rayleigh path.

In conclusion, we have developed and demonstrated an extremely powerful technique for differential phase measurement. The same technique can be scaled in physical dimensions as well as in frequency for other applications. We have also constructed a very useful measurement system which can produce both qualitative and quantitative images. We foresee a number of applications in the area of nondestructive testing.

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