MEASUREMENTS OF LOCAL SURFACE WAVE SPEEDS BY A DUAL-PROBE LASER INTERFEROMETER

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INTRODUCTION

In a recent paper Huang and Achenbach[1] have reported the development of a dual-probe laser interferometer. In addition to the usual advantages of a laser interferometer such as no contact and point detection, the dual-probe interferometer measures the same signal at two points along its propagation path. Hence the instrument is particularly useful for the measurement of surface wave speed and attenuation. Such measurements provide valuable information on the near-surface material properties as well as the condition of the surface.

In ref. [1] the distance between the two probes was taken relatively large, so that the two measured waveforms did not overlap. In this paper a small distance between the two probing beams is used to obtain a better measure of the local surface wave speed. Now the signals overlap, and the power cepstrum signal processing method has been used to obtain the time of flight between the two points.

As an example of the use of the dual-probe interferometer the surface wave speed was measured as a function of direction of propagation on the (001) plane of a single crystal silicon plate. A surface wave transducer was used to generate the surface wave signal. After signal processing using the power cepstrum method, the speeds of the regular Rayleigh surface wave and the pseudo surface wave were obtained. The experimentally obtained surface wave speeds have been compared with theoretical calculations and acoustic microscope measurements, and very satisfactory agreement has been observed.

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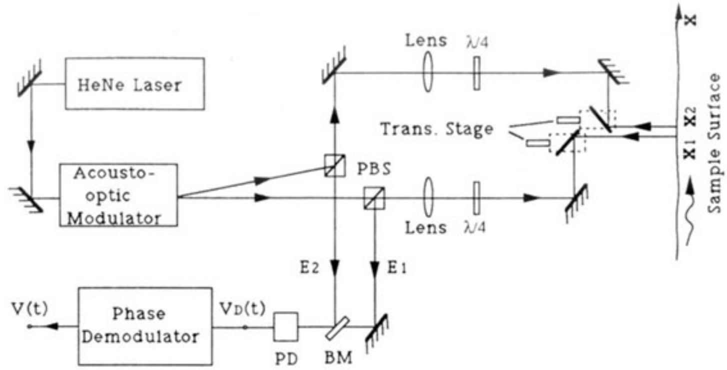

Fig. 1. Diagram of the differential dual-probe laser interferometer.

PRINCIPLE OF THE DUAL-PROBE DIFFERENTIAL INTERFEROMETER

The diagram of the dual-probe differential laser interferometer, which is shown in figure 1, has been discussed by Huang and Achenbach[1]. As can be seen from the diagram, the HeNe laser is modulated by an acousto-optic modulator. The zeroth order and the first order beams are used as the the two probes of the interferometer. In a single probe heterodyne laser interferometer, the frequency shifted beam acts as a reference beam which goes to a reference mirror instead of the specimen as discussed by Monchalin[2,3]. In this dual-probe differential interferometer, both beams go to the specimen surface.

As discussed in Ref. [1] the phase demodulation unit produces a voltage proportional to the difference of the displacements at the two detection points,

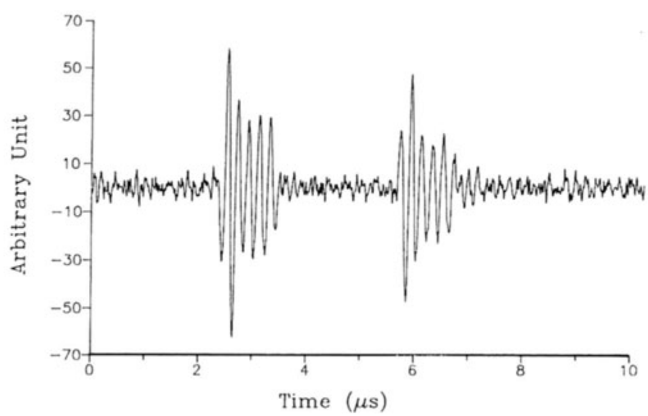

Fig. 2. Surface wave train detected by the dual-probe laser inter-interferometer when the separation of the two probes is larger than the wave train so that the two waveforms are separated in the time domain.

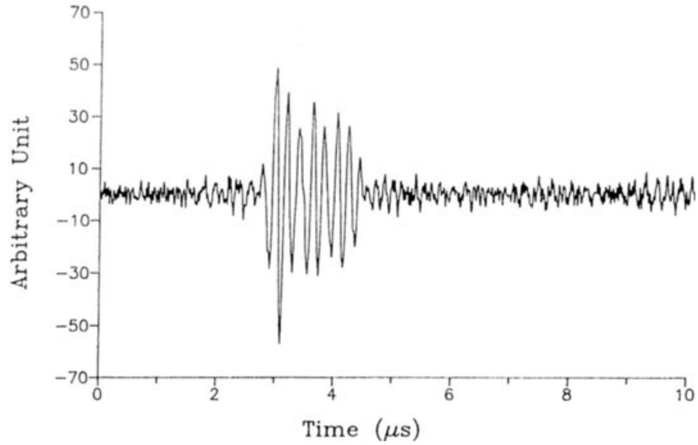

Fig. 3. Surface wave trains detected by the dual-probe laser interferometer when the separation of the two probes is shorter than the wave train so that the two waveforms overlap.

$$V(t)=C[v(t,x_1)-v(t,x_2)] \quad (1)$$

where C is a calibration constant. In the experiments reported here, C is 0.59 mV/nm.

Equation (1) shows that when the separation between the two beams is bigger than the length of the surface wave pulse, then V(t) directly gives the surface wave at the two detecting points, except that the second signal should be reversed in sign to get $v(t,x_2)$. This case is shown in figure 2 where the separation is 16.22mm. The reduction in the amplitude of the second signal is caused by the spreading of the surface wave since it is generated by a transducer with finite width.

When the separation of the two beams is small compared to the length of the surface wave, a composite signal is obtained as shown in figure 3, where the two probes are separated by 2.745mm. In this case in order to find the delay time between the two signals, a signal processing technique must be employed to resolve $v(t,x_1)$ and $v(t,x_2)$ from the composite signal V(t).

THE POWER CEPSTRUM METHOD

The power cepstrum method is a signal processing technique to find the delay times of a train of pulses[4]. For the problem at hand there are only two pulses, one from each probe.

Assuming that dispersion of the signal is negligible, and that the loss from wave diffraction may be accounted for by a constant factor r, then the composite signal can be written as

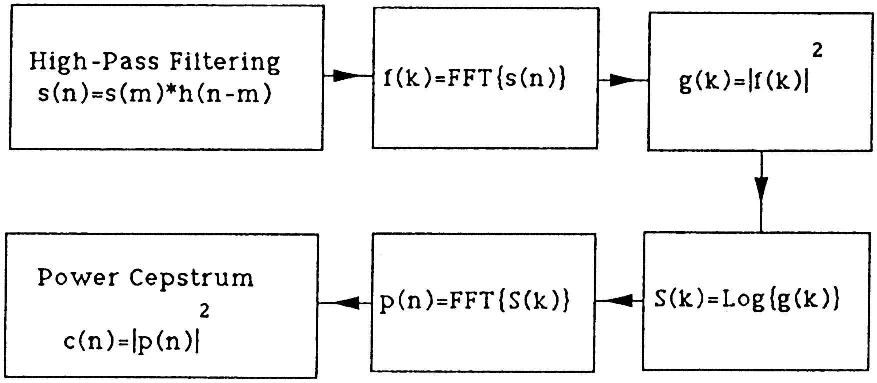

Fig. 4. Schematic of the algorithm for the power cepstrum calculation.

$$V(t)=v(t)+rv(t-\tau) \qquad (2)$$

where τ is the travel time between the two detecting points. For this experiment we have $-1<r<0$ since the second pulse is reversed in sign and has a smaller amplitude than the first signal.

The procedure to calculate the power cepstrum is illustrated in figure 4. In this experiment, there is a low frequency variation in the signal output from the dual-probe interferometer, which causes a discontinuity at both ends of the signal and introduces a windowing error when the Fourier transform is applied. Therefore, a digital low-pass filtering is applied prior to the cepstrum calculation to remove the low frequency variation and to achieve better accuracy in the cepstrum. Application of the cepstrum procedure yields

$$S(f)=2\log|F(f)|+\log[1+r^2+2r\cos(2\pi f\tau)] \qquad (3)$$

where S(f) is the logarithm of the power spectrum of V(t) and F(f) is the spectrum of v(t).

When $|r|$ is much smaller than unity, an expansion of the second term of Eq.(3) gives

$$S(f)=2\log|F(f)|+2r\cos(2\pi f\tau)+o(r) \qquad (4)$$

where o(r) represents the terms with higher orders of r. From Eq.(4), it can be seen that S(f) is basically a harmonic ripple with a periodicity of τ, superimposed on a logarithmic flattened power spectrum of the original pulse v(t). After an inverse Fourier transform back to the time domain(referred to as quefrency domain by some authors), the logarithmic flattened term $\log|F(f)|$ contributes mainly to the time region close to origin while the periodicity in the cosine term appears as a spike with delay time τ .

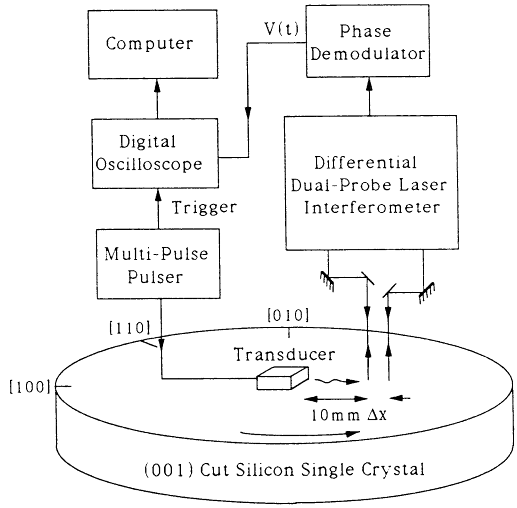

Fig. 5. Configuration of the experiment for measurement of the surface wave speed on a single silicon crystal.

In the present case |r| is not small. However the second term in Eq.(4) still displays periodic behavior, which after a Fourier transform back to the time(quefrency) domain, gives rise to a principal spike and a number of smaller ones.

EXPERIMENTAL PROCEDURE

The experimental configuration is shown in figure 5. The specimen is a single crystal silicon plate of diameter 4.0 in. and thickness 1.0 in., and the two flat surfaces are (001) planes of the crystal. They are polished to 25 micron finish. The surface wave is generated by a piezoelectric surface wave transducer with 5 MHz center frequency. The source is a multi-pulse generator tuned to an appropriate delay time between the pulses to form tone-burst trains. Pulse trains consisting of different numbers of pulses were considered. It was found that in the power cepstrum a longer pulse train has a better signal to noise ratio than a shorter train , even though the signals overlap more in a longer pulse train. A pulse train with five pulses has been used in the experiment. The signal is acquired by a digital oscilloscope and transmitted to a computer. Data is taken for surface wave propagation relative to the crystalline direction.

Two examples of the surface wave measurements are shown in figure 2 and figure 3 for propagation in the [100] direction. Figure 2 shows the signals when the two probes are separated by 16.22mm, while the separation distance in figure 3 is 2.745mm. The later is about the minimum separation distance due to limitations of the mechanical structure of the interferometer. The travel time in figure

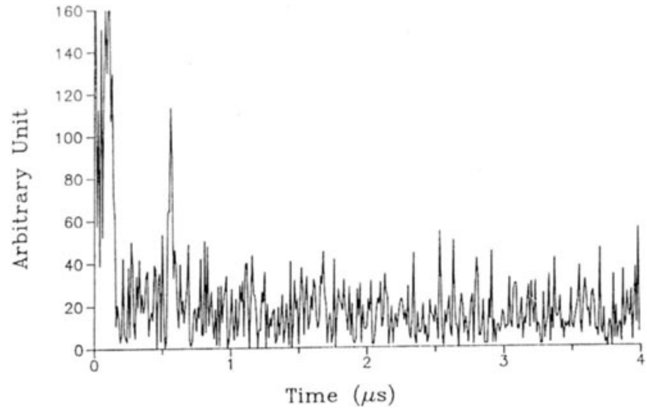

Fig. 6. The power cepstrum for propagation in the [100] direction.

2 can easily be measured by peak to peak time or by the maximum in its autocorrelation. In figure 3, the travel time can not be found by either of these methods. The power cepstrum method has to be employed for the results of figure 2. Figure 6 shows the power cepstrum of the composite signal of figure 3. The travel time is given by the distinct spike. Dividing the distance between the two probes by the travel time yields the surface wave speed.

RESULTS AND DISCUSSION

It is well known that on the plane surface of a homogeneous, anisotropic, linearly elastic solid, a regular Rayleigh wave can propagate with a speed that depends on the wave propagation direction. In addition, in certain directions a pseudo surface wave can propagate[5]. For propagation on the (001) plane of a single silicon crystal, the speeds of these waves have been calculated and they are shown in figure 7[6] It is noted that the curve for the Rayleigh wave

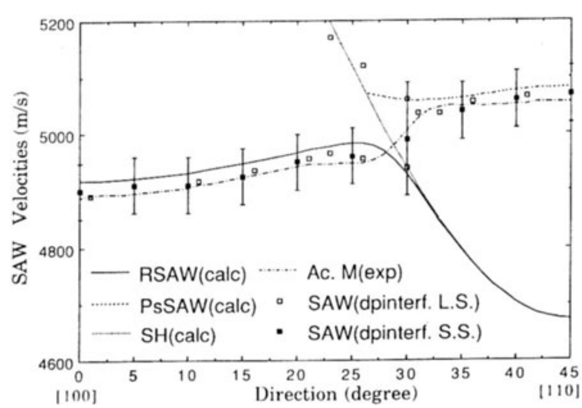

Fig. 7. Curves of surface wave velocities versus direction of propagation on the (001) plane of a silicon crystal.

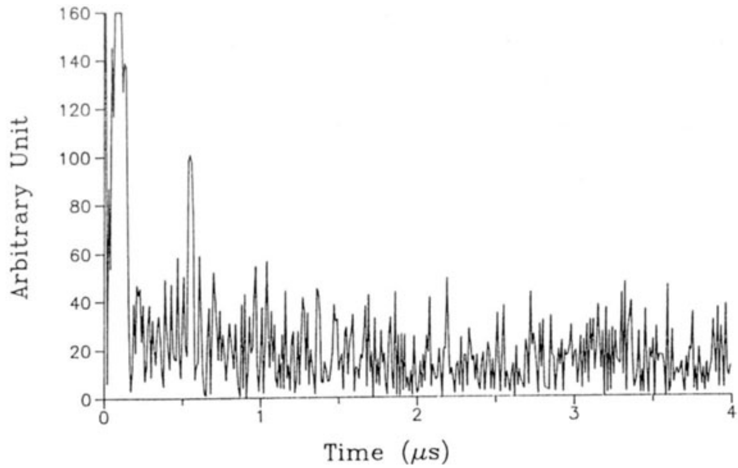

Fig. 8. The power cepstrum for propagation in the 30 degree direction.

speed merges into the speed of the horizontally polarized shear wave as the propagation direction approaches the [110] direction, which is 45 degrees in the present case. The displacement of the Rayleigh wave is in the sagittal plane when the propagation is in the [100] direction, but a horizontal displacement component starts to develop, which increases in mangnitude as the propagation direction approaches the [110] direction. As the angle increases the displacement becomes totally horizontal with no vertical component just like a bulk horizontal shear wave. On the other hand, for propagation in the [110] direction, the displacement of the pseudo surface wave lies completely in the sagittal plane like a regular Rayleigh wave. As the propagation direction turns away from [110] its horizontal displacement increases and the vertical displacement decreases until it vanishes.

Since the dual-probe interferometer is sensitive only to the out-of-plane displacement, it can pick up only the regular Rayleigh wave in the range from 0 to about 35 degrees and the pseudo surface wave in the range from 25 to 45 degrees. Beyond those ranges the vertical displacement is too small for the interferometer to be detected. In the region from 27 to 33 degree, both types of surface waves have vertical displacements of the same order of magnitude. This region may be called a "transition region". In the transition region, the dual-probe interferometer output should have four overlapping signals.

Figure 7 also shows the velocities measured with the acoustic microscope and with the same dual-probe laser interferometer but with a large separation of the two probes. The experimental results agree very well with the theoretical calculations outside the transition region. Inside the transition region, the acoustic microscope gives an averaged value of the two wave speeds while the dual-probe interferometer gives both values.

The measurement by the dual-probe interferometer with a small probe separation is also shown in figure 7. In order to pick up the surface wave before it curves away from the transducer axis where the measurement is made, the detecting points can not be too far away from the transducer. The first probe is placed about 15mm from the surface wave transducer, so in the transition region where the two waves have similar amplitudes the two surface waves are not separated. Consequently there are four overlapping waves in the interferometer output signal. Outside the transition region the results agree with theory and experimental results from other techniques. It is estimated that the measured results have an accuracy of 0.8%. Inside the transition region, the results are close to the result of the acoustic microscope measurements, but a bigger error is observed. The power cepstrum for propagation under 30 degrees is shown in figure 8. Two spikes related to the two different travel time should be found if the sampling time was small enough, but only one is actually observed. The width of the spike is indicative of the error of the velocity. The error range includes, however, the two theoretical velocities of the two types of surface waves.

In summary, it has been shown that a dual-probe differential laser interferometer provides accurate noncontact measurements of the local surface wave speed. The power cepstrum method was found to be an efficient technique for the determination of the wave speed.

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