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ULTRASONIC WAVES IN SANDWICHED FLUID FILM

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ULTRASONIC WAVES IN SANDWICHED FLUID FILM

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ABSTRACT

Using optical diffraction, we have measured the phase velocities of various ultrasonic modes in water films of different thicknesses sandwiched between two glass plates. The results agree well with theory.

†On leave at the Miller Institute of University of California.

Acoustic wave propagation in layered media has been studied quite extensively.[1] In particular, sound propagation in fluid sandwiched between two solid plates has attracted much attention because of its applications in delay line[2] and in coupling of surface waves between separate surfaces.[3] Two kinds of modes exist in the fluid film: the waveguide modes and the surface-like modes.[1] So far, only the group velocities of the waveguide modes have been measured.[2] The phase velocity, however, is a more fundamental quantity. We present here what we believe to be the first direct phase velocity measurements of both the waveguide and the surface-like modes in fluid films between solid plates. Our results are in good agreement with theoretical calculation.

Figure 1 shows our experimental arrangement. We have studied water films of various thicknesses sandwiched between glass plates. An ultrasonic Rayleigh wave at 12.3 MHz was first generated on a Y-cut X-oriented quartz

plate by an interdigital surface wave transducer and then transferred through a water coupler[3] onto one of the glass plates binding the film. The thickness of the film was uniformly controlled to ± 2 μm by mylar or Al spacers. The inner surface of one of the glass plates was coated with a thin (~ 500Å) Al film so that the propagating sound waves would corrugate the film into a reflective grating. A 1.5 mW laser beam of 5 mm in diameter was used to probe the corrugation which caused a diffraction of the reflected light.[4] The diffracted beam was focused by a lens onto a focal plane as shown in Fig. 1. It was then detected and analyzed by a photomultiplier behind a .2 mm × 2 mm slit sitting on a rail. The position of the slit on the rail was read by a potentiometer whose output was fed to the x-terminal of an x-y recorder. With this setup, the diffraction peaks could be easily separated from the central reflection peak. In order to improve the signal-to-noise ratio, we modulated the acoustic wave amplitude and used the phase-sensitive scheme to detect the diffracted beam. The output from the lock-in unit was sent to the y-terminal of the recorder.

A typical diffraction pattern is shown in Fig. 2. In this case, corresponding to 182 μm film thickness, five sets of diffraction peaks can be distinguished. They resulted from five different acoustic modes in the film as we will discuss later. The peak height is proportional to the square of the lateral amplitude of the corresponding acoustic mode at the Al film. The phase velocity of these modes can be deduced from the position of the diffraction peaks. We used a thick (~ 1 mm) water film, for which the outermost diffraction peak was due to an acoustic mode with essentially the bulk wave velocity (~1.485 km/sec),[5] to calibrate the phase velocity measurements. As a check, we measured the Rayleigh

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wave velocity on quartz to be 3.14±0.03 km/sec, in good agreement with the value in Ref. 4. We also found the Rayleigh wave velocity on glass to be 3.11±0.03 km/sec in agreement with a calculated value of 3.09 km/sec deduced from the measured bulk sound velocities in glass. We have measured the phase velocities of all the acoustic modes in the sandwiched water film as functions of film thickness. Our results are shown in Fig. 3.

Theoretically, the acoustic modes in a fluid film are described by[2]

$$\frac{1}{\rho}\left(\frac{c_t}{c}\right)^4 \left[\frac{(c/c_f)^2 - 1}{1 - (c/c_l)^2}\right]^{1/2} \left\{4\left[1 - \left(\frac{c}{c_l}\right)^2\right]^{1/2} \left[1 - \left(\frac{c}{c_t}\right)^2\right]^{1/2} - \left[2 - \left(\frac{c}{c_t}\right)^2\right]^2\right\} = \tan\left\{kh\left[\left(\frac{c}{c_f}\right)^2 - 1\right]^{1/2}\right\} \quad \text{for odd modes}$$

$$= -\cot\left\{kh\left[\left(\frac{c}{c_f}\right)^2 - 1\right]^{1/2}\right\} \quad \text{for even modes} \qquad (1)$$

where ρ is the mass density ratio of fluid to solid, c and k are the phase velocity and wave vector of the acoustic mode respectively, c_f is the sound velocity in fluid and c_l and c_t are respectively the longitudinal and transverse sound velocities in solid. The solid boundary planes are at $z = \pm h$. We can have $c > c_f$ or $c < c_f$. The modes with $c > c_f$ are the waveguide modes which could be envisaged as bulk longitudinal sound waves bouncing back and forth between the two solid planes. They reduce to the free Rayleigh wave on solid in the absence of the fluid. The modes with $c < c_f$ are the surface-like modes. In the case of a single solid-fluid interface they reduce to the so-called Stonely mode[6] which decays exponentially on both sides of the interface.

We measured c_l and c_t in glass plates to be 5.69 km/sec and 3.38 km/sec respectively. The mass density of the glass plates was 2.45 gr/cm^3. Then, with c_f = 1.49 km/sec and ρ = 2.45, we solved Eq. (1) numerically. The result is shown in Fig. 3 as solid curves. Note that there is no adjustable parameter in the calculation. The agreement is quite good. The small discrepancy is presumably due to the fact that in deriving Eq. (1), we have neglected the boundary layer in the fluid where visco-elasticity is important. The odd surface-like mode is absent in Fig. 3 because the cutoff thickness for this mode is about 450 μm.

The relative intensities of the various modes depend of course on the boundary conditions at the feeding edge and should vary with the film thickness. As the thickness was increased, the fastest guided mode grew in amplitude at the expense of the slower modes until a new and even faster mode set in. In this manner, most of the acoustic power was in the mode with a phase velocity close (but not necessarily closest) to the free Rayleigh wave velocity. This behavior is reasonable considering the large acoustic impedance mismatch of the slower modes with the free Rayleigh wave at the feeding edge.

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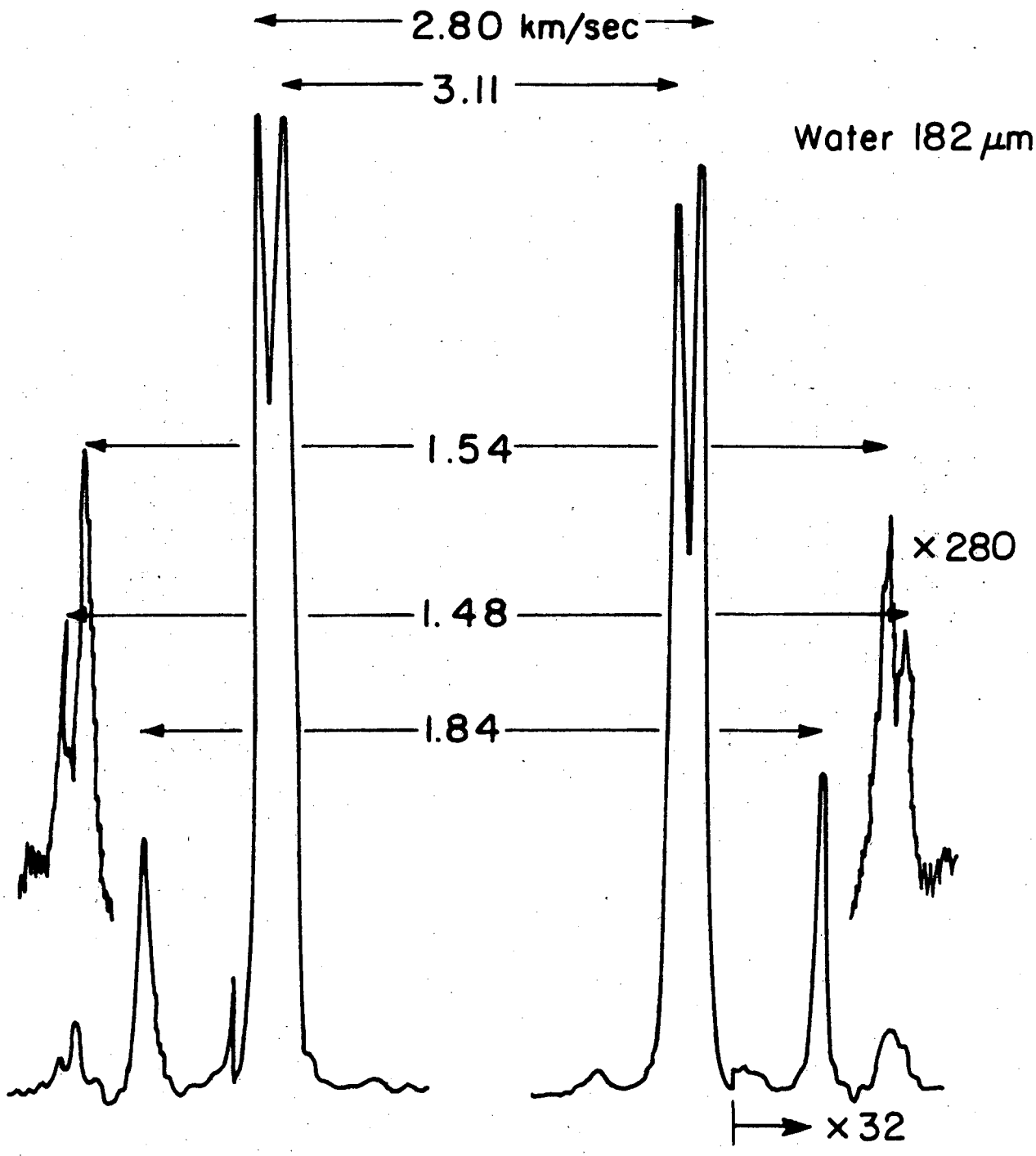
FIGURE CAPTIONS

Fig. 1. Block diagram of the experiment.

Fig. 2. Typical diffraction pattern from acoustic waves in a 182 μm water film held between glass plates. The peak separations indicated are inversely proportional to the phase velocities of the acoustic modes.

Fig. 3. Thickness dependence of the phase velocities of various acoustic modes in water films between glass plates. WE: even waveguide modes, WO: odd waveguide modes, and SE: even surface-like mode. Dots are experimental data and solid curves are calculated from Eq. (1).



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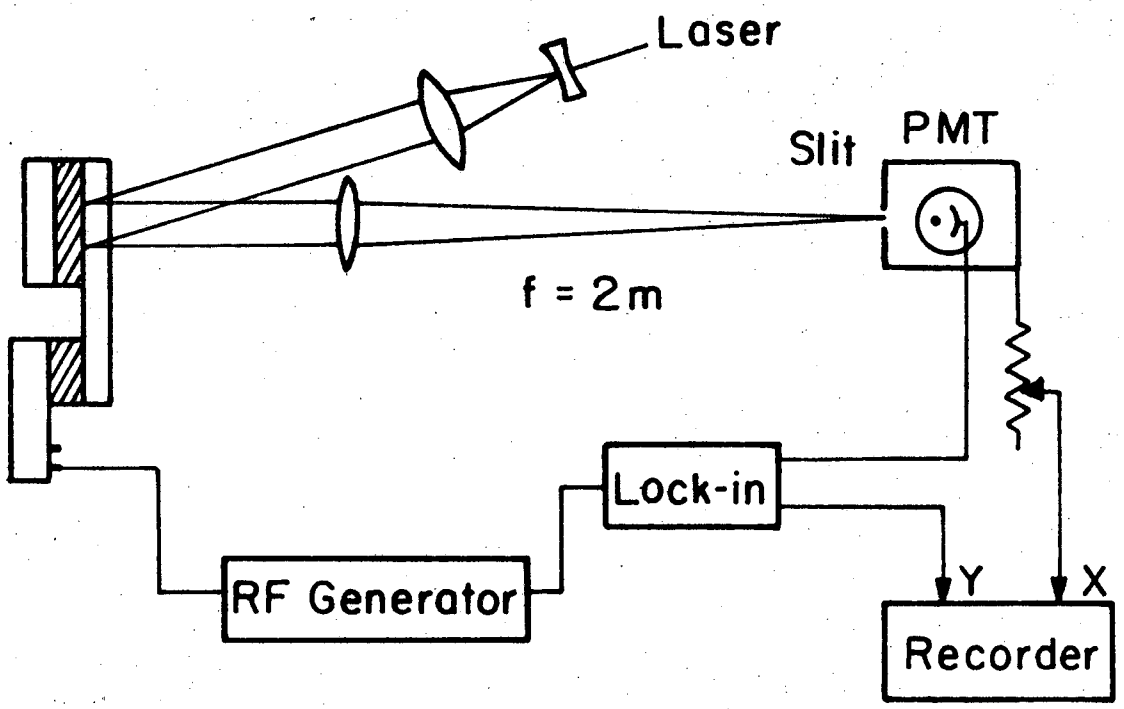

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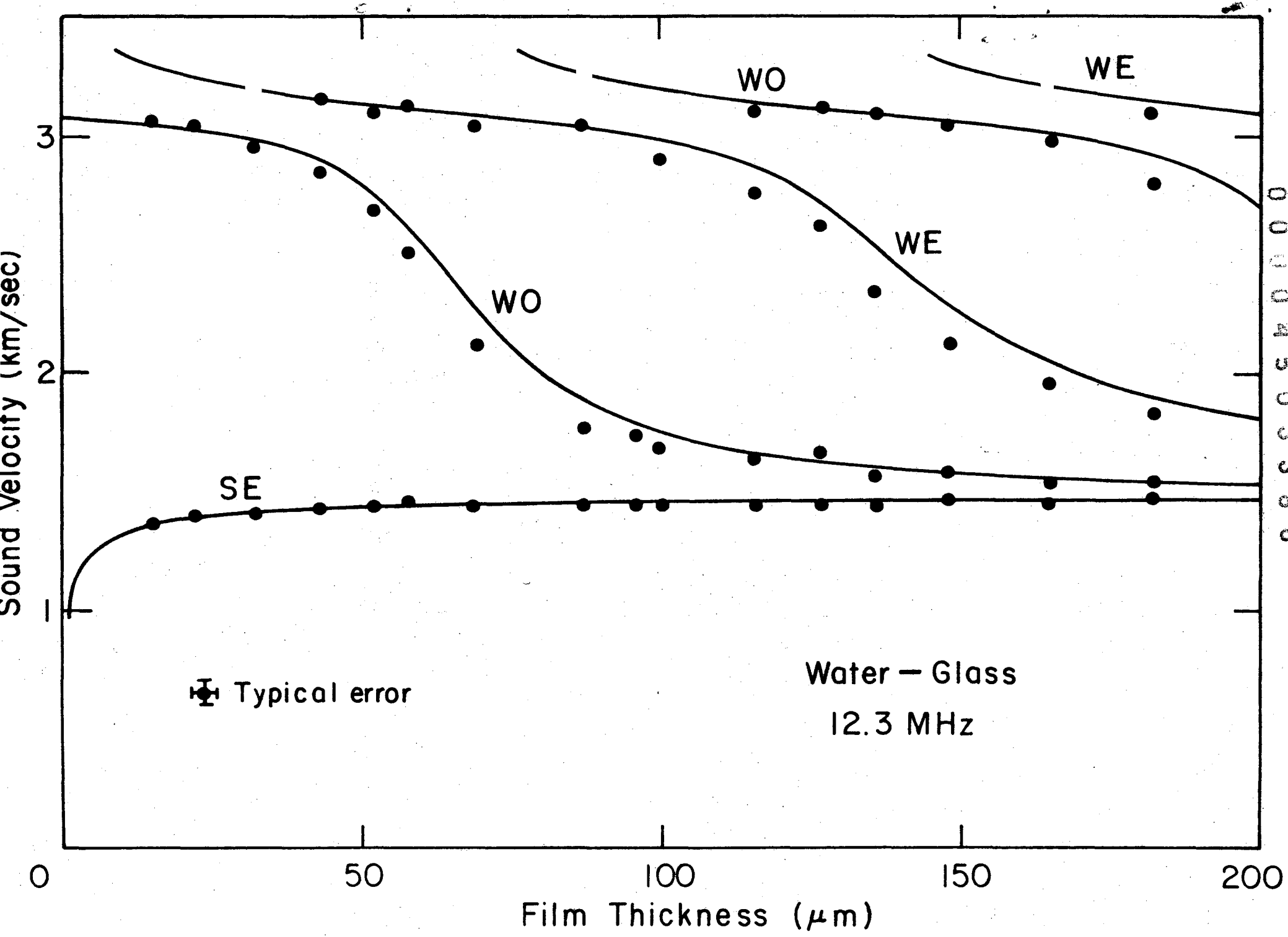
WO
WE
WE
WO
SE
Typical error
Water — Glass
12.3 MHz
Sound Velocity (km/sec)
3
2
1
0
50
100
150
200
Film Thickness (μm)

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