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Use of Bragg-Diffraction Imaging for Acoustic Velocity Measurement

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Acoustic velocities in platelike elastic materials satisfying certain conditions can be measured by irradiating the materials with ultrasound and processing the ultrasonic transmission patterns with laser light to obtain Bragg diffraction of the light. Simple observation or measurement of the diffracted optical image as the acoustic frequency is varied gives both compressional and shear-wave velocities through the materials. A real-time visualization of the acoustic transmission pattern can also be obtained. This method provides a simple means of detecting inhomogeneities in platelike material and obtaining a quantitative comparison of the velocity characteristics with reasonable precision in localized regions.

INTRODUCTION

Bragg-diffraction imaging[1–3] provides a unique way of processing information contained in an acoustic field. This capability allows many useful extensions, one of these being the measurement of acoustic velocity in selected portions of the object being imaged.

The experimental setup for acoustic velocity measurement is essentially the same as that for conventional transmission-mode Bragg-diffraction imaging. A typical arrangement for Bragg-diffraction imaging is shown in Fig. 1. If an acoustic transparency in the form of a plate (i.e., with parallel front and back surfaces and lateral dimensions much greater than the thickness) is placed in the cell, the opacity or the transparency of the Bragg-diffracted visual image depends on both the acoustic frequency and the angular orientation of the plate about a vertical axis. With proper orientations, simple observation or measurement of the Bragg-diffracted image as the acoustic frequency is varied gives data that can be easily used to calculate both the compressional and the shear-wave velocities in the plate.

I. ANALYTICAL CONSIDERATIONS

One method of explaining the behavior of the sound when the plate is transparent is with an electrical analog. Consider an infinite plate of lossless elastic

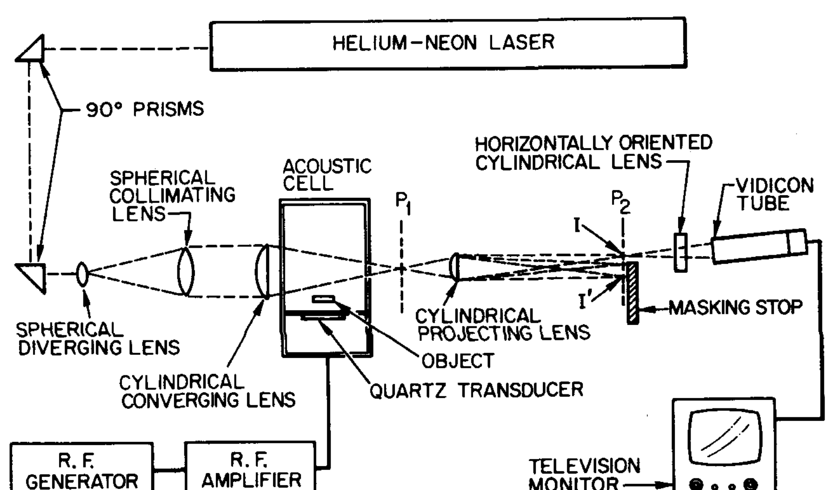

Fig. 1. Schematic diagram of the Bragg-diffraction imaging system.

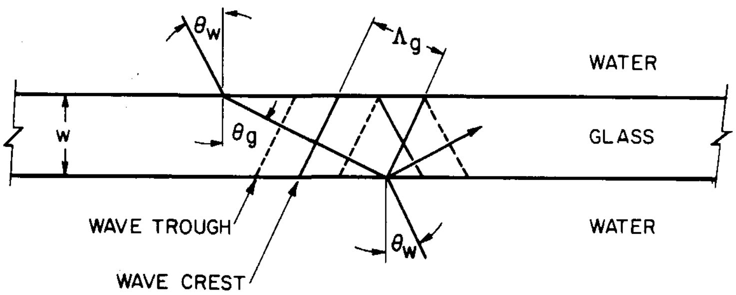

FIG. 2. Acoustic wave propagation through a glass plate in water.

material insonified by a plane wave of sound. For arbitrary angular positions of the plate, both compressional waves and shear waves are excited in the plate. With the proper orientation of the plate, it is possible to launch a shear wave without exciting a compressional wave, or vice versa.[4] Under the circumstance that only one kind of wave is present in the plate, an electrical transmission-line concept can be applied to describe the propagation behavior. The propagation of the acoustic wave through the water, into and through the plate material, and then out of the plate and back into the water, is analogous to that of an electromagnetic wave in a lossless transmission line through a dissimilar section located in the middle of the line. If the length of this middle section is a multiple of a half-phase wavelength, the transmission through the section is complete, entailing no reflections or losses. Thus the dissimilar section appears transparent to the propagation.

Figure 2 depicts the above situation with glass as the plate material and water as the medium. Assume that θ_w is the angle of incidence of the acoustic plane wave that excites only one kind of acoustic wave in the glass plate. Maximum transmission through the glass plate occurs when the thickness of the plate, w, is a multiple of a half-phase wavelength in the plate, Λ_p. Thus the plate appears acoustically transparent when

$$w = N\Lambda_p/2, \tag{1}$$

where N is an integer.

Snell's law relates the acoustic velocity in water V_w the shear wave or compressional wave veolcity (depending on which one is being generated) in glass V_g, the angle of incidence θ_w, and the angle of refraction θ_g:

$$V_w/\sin\theta_w = V_g/\sin\theta_g. \tag{2}$$

Two other basic relations used are

$$V_g = f\Lambda_p, \tag{3}$$

$$\Lambda_p = \Lambda_g/\cos\theta_g, \tag{4}$$

where f is the acoustic frequency and Λ_g is the wavelength in the glass plate. The above four equations are essential in establishing the procedure for the measurement of acoustic velocity in the plate.

A Bragg-diffraction imaging system is employed to determine how transparent the plate is to the acoustic waves. The degree of transparency can easily be found either by visually observing the brightness of the Bragg-diffracted image of the plate's silhouette as compared with the brightness of the Bragg-diffracted image of the background transducer, or by probing the diffracted-light field with a pinhole and a photomultiplier set. The latter procedure can give a more accurate measurement.

It has been mentioned that the transmission-line analogy and the resulting equations are applicable only when either compressional waves or shear waves are excited in the plate. Pure compressional-wave generation can be guaranteed for normal incidence onto an ideal plate. Pure shear-wave generation occurs at a different angle of incidence which is not known in advance without the knowledge of the shear-wave velocity.[4] For other orientations of the plate, both types of waves are simultaneously excited. However, even with both kinds present, the plate can appear acoustically transparent if the angle of incidence and the sound frequency are in the proper relationship. Since transmission peaks are being measured as the sound frequency is varied, the lack of advance knowledge of the proper orientation complicates the measurement of the shear-wave velocity.

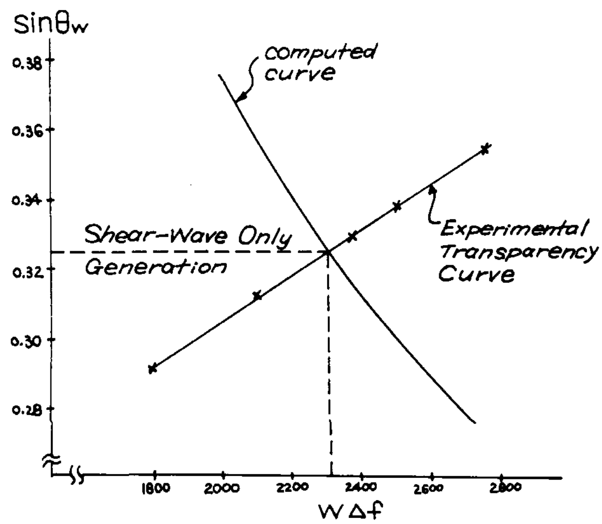

FIG. 3. Superposition of the computed curve and the experimental plot.

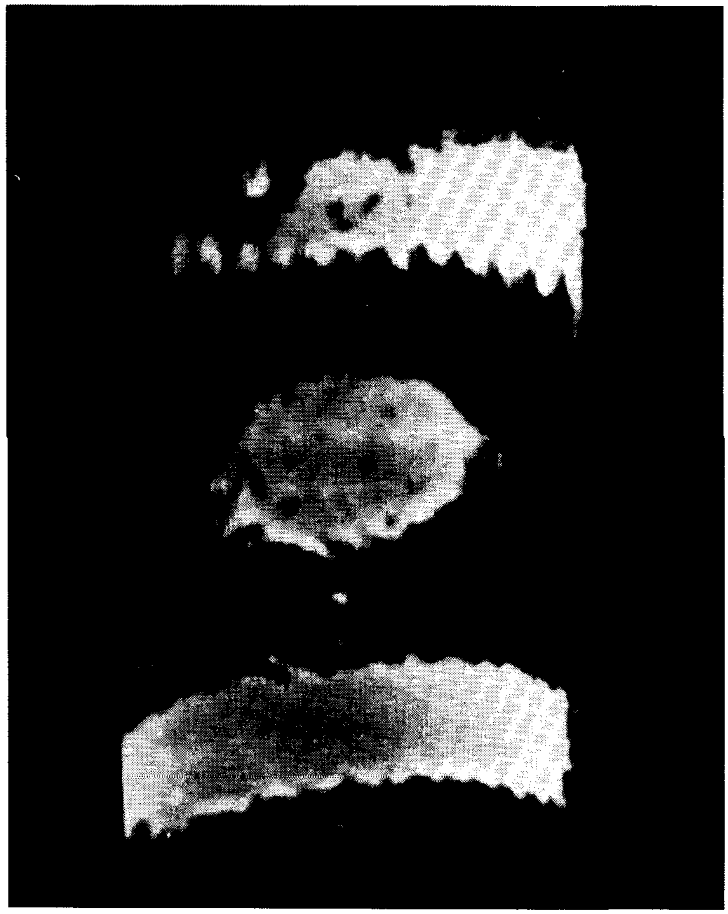

FIG. 4. Bragg image of the stainless-steel plate with the aluminum plug appearing transparent.

By using the Bragg-diffracted image of the object to observe and measure this transparency, quick quantitative measurements may be combined with over-all acoustic inspection of an object. The acoustic image of the entire object may be inspected and then measurements made in smaller localized regions of interest that meet the conditions of having a platelike structure.

Compressional-wave velocity V_c is measured with the plate oriented normally to the sound. This orientation can be determined precisely by obtaining angularly symmetric transmission peaks about the normal incidence position. Once the sound propagation is oriented perpendicularly to the object, the frequency of the sound is continuously changed and the acoustic transmission in the area of interest is measured with Bragg-diffraction imaging. Two adjacent frequencies, f_1 and f_2, are found for which the silhouette of the plate disappears (indicating complete transparency). From Eqs. 1, 3, 4, and $\theta_g=0$, we can write

$$NV_c=2wf_1, \tag{5}$$

$$(N\pm1)V_c=2wf_2. \tag{6}$$

Subtracting Eq. 5 from Eq. 6, we obtain

$$V_c=2w|f_1-f_2|. \tag{7}$$

With the measurement of f_1 and f_2 and the knowledge of the plate thickness, we can use Eq. 7 to calculate the compressional-wave velocity.

Shear-wave velocity measurement requires a somewhat longer procedure. As pointed out by Fay and Fortier,[4] for the angle of incidence θ_w that generates only shear waves in a plate, the wave motion induced in the plate is made up of two equal shear waves traveling at right angles to each other and having an angle of refraction θ_g of 45°. Assume that f_1 and f_2 are two adjacent frequencies for which the silhouette disappears for this incidence angle θ_w. By combining Eqs. 1, 3, and 4 and letting $\theta_g=45°$, the following expression for the shear-wave velocity V_s is derived:

$$V_s=1.4w|f_1-f_2|. \tag{8}$$

Substitution of Eq. 8 and $\theta_g=45°$ into Eq. 2 yields

$$\sin\theta_w=V_w/(2w|f_1-f_2|). \tag{9}$$

Note that Eqs. 8 and 9 hold only when shear waves alone are excited. Without knowledge of this θ_w in advance, it becomes necessary to make a series of measurements involving different angles of incidence and to use a graphical method to obtain the shear-wave velocity. The experimental procedure is as follows:

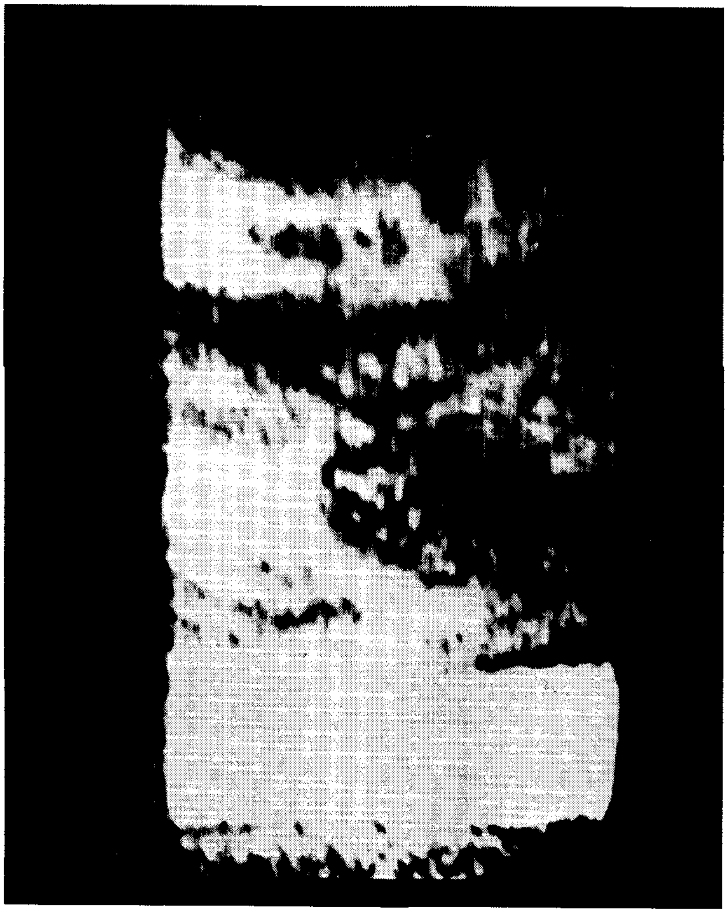

FIG. 5. Bragg-diffracted image of the stainless-steel plate with the aluminum plug appearing opaque.

Choose a range of angles of incidence to cover the estimated θ_w (less than 45°). For each chosen angle of incidence θ, obtain two adjacent frequencies, f_1 and f_2, for which the silhouette of the plate disappears. With the measured thickness of the plate, w, and the experimental data, make a plot of $\sin\theta$ vs $w|f_1-f_2|$. Using Eq. 9 and the known sound velocity in water, obtain another plot of $\sin\theta_w$ vs $w|f_1-f_2|$. With the two plots superimposed as in Fig. 3, the intersection gives the correct angle of incidence θ_w and the corresponding value of $w|f_1-f_2|$ to be used in Eq. 8 to calculate the shear-wave velocity.

TABLE I. Comparison of experimental results and published values.[a]

	Compressional wave velocity	Shear-wave velocity
In aluminum:		
Experimental	6340 m/sec	3160 m/sec
Published	6420 m/sec	3040 m/sec
In stainless steel:		
Experimental	5740 m/sec	3250 m/sec
Published	5790 m/sec	3100 m/sec

[a] See Ref. 5.

Strictly speaking, the foregoing argument is true only when the plate has infinite lateral extent. However, as long as the geometrical irregularities (finiteness of the plate's lateral dimensions, etc.) have negligible effect on the infinite plane-wave solution in the region of interest, our assumptions can still be considered valid for practical purposes. Therefore, the method described can be applied to measure the acoustic velocity in a finite plate or a finite platelike region of an object, if the area of interest has dimensions much larger than the acoustic wavelength.

II. EXPERIMENTAL RESULTS

The validity of this approach and the utility of the method can be demonstrated experimentally by simulating an inhomogeneity in a plate with a plug of dissimilar material. A circular aluminum plug ($\frac{1}{4}$ in. in diameter) in a stainless-steel plate ($\frac{1}{16}$ in. thick) was used. Compressional and shear-wave velocity components in both the plug and the plate were measured. Photographs of the real-time visualization of the acoustic transmission pattern are shown in Figs. 4 and 5 with the plug and the plate appearing transparent in turn. For compressional-wave velocities, 5740 m/sec was obtained in stainless steel and 6340 m/sec in aluminum.

For shear-wave velocities, 3250 m/sec was obtained in stainless steel and 3610 m/sec in aluminum. A comparison with published values[5] is shown in Table I.

The success of acoustic velocity measurement by Bragg-diffraction imaging depends upon the conformity of the actual situation with our preceding assumptions. A good broad-band transducer with small losses is required. Usually simple eye observation of the Bragg-diffracted image on the television monitor yields fair accuracy. To improve the accuracy, better means of probing the diffracted-light field (for instance, the use of a pinhole and a photomultiplier) must be provided to obtain more precise measurements of transmission peaks. The processing of the information contained in the diffracted-light field determines the quality of the experimental results and hence the accuracy of the method could be improved by more detailed measurements and processing.

III. CONCLUSIONS

This procedure for velocity measurement provides a simple means of obtaining a real-time visualization of inhomogeneities and quantitative velocity characteristics with reasonable precision in platelike regions of interest of the sample. The method does not appear to compete in accuracy and precision with existing methods for a homogeneous plate, but it does have the advantage of simplicity and flexibility. This is especially true in the case of large plates in which local inhomogeneities are present and must be detected. With this approach quantitative information concerning the inhomogeneities can be extracted.

ACKNOWLEDGMENT

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