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presented. A two-layer solid medium immersed in water is solved to illustrate the effect of an incident p-wave on the refraction and reflection properties.

Theoretical properties of acoustical speckle interferometry are discussed which includes the effect of deformation. A data analysis procedure is described which utilizes a two-dimensional correlation of acoustical signals as a direct measure of object motion. Numerical examples are presented to illustrate the correlation of reference and deformed ultrasonic signals. Uniform translations without geometric distortion are presented. Geometric distortions for both infinitesimal and finite deformations are illustrated to show this effect on the deformed acoustical surface. All results are presented in graphical form.

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## I. INTRODUCTION

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Research areas in experimental mechanics have been greatly expanded since the introduction of the He-Ne laser in 1960. Initial engineering applications utilized holographic interferometry to measure surface deformations of opaque solids. Original applications suggested that the modern techniques in coherent optics would possibly change the method of measurement of strains and stresses; however, this has not been the case, although many engineering examples have been successfully demonstrated. Some of the authors' contributions are listed in references [1-7]. Although interference fringes are well defined in holography, difficulties exist because of the sensitivity of the measurements which require vibration isolation and the ability to separate displacement components from a single hologram. Thus, holography has not developed as a general technique of experiemtal stress analysis, and still remains a technique of the specialist.

Objects illuminated with coherent light are observed to have a granular appearance known as the laser speckle effect. The details of this structure do not resemble the microscopic character of the surface, but rather appear to be random in nature. This effect is described in terms of the interference of the microscopic nature of the surface when illuminated with a laser. Interference of the dephased, but coherent, waves results in this speckle effect[8]. This effect has provided for a method of surface displacement measurements known as laser speckle interferometry, which does not require vibration isolation. In addition, this technique is a direct measure of in-plane displacements; thus, the separation of components is accomplished easily [7]. All coherent optical methods are a measure of surface displacements or its derivatives on the boundary of a solid; thus, the need still exists to calculate stresses and strains at any desired point in a three-dimensional body from the surface data.

The concept of speckle was first applied to optical systems; however, modern applications reveal that the speckle effect occurs in many areas of physics and engineering [8-10] as a result of the ubiquitous character of the random interference phenomenon. Examples of analogies to the laser speckle effect include radar astronomy, synthetic aperture radar, recent developments in ultrasonic holography, and theory of spectral analysis of random processes. Goodman [8] illustrates that the basic concepts of speckle are much broader than originally envisioned with the laser, and that the results apply to all related phenomena, so long as the basic statistical assumptions are satisfied. Because of these parallels, the results of the laser speckle effects in optics suggest the possibility of an acoustical speckle effect utilizing ultrasonics. The direct extension of substituting an ultrasonic wave for coherent light is an obvious one, since it was first performed in the acoustical holography. An acoustical speckle interferometry study has been demonstrated to be a direct measure of object motion [11,12], which closely parallels laser speckle interferometry. The particular significance of the ultrasonics is the fact that subsurface scattering points can be recorded and correlated to measure acoustical signals. Thus, acoustical speckle interferometry has the potential to measure displacements of interior points in opaque solids. The extension to include measurements of deformable bodies will result in a technique to measure directly strains at interior points in otherwise opaque solids.

## II. ELASTODYNAMIC THEORY

Acoustical speckle interferometry is based locally on the elastodynamic response of solids subjected to ultrasonic waves. The basic theory will be governed by the following set of field equations for a homogeneous isotropic medium.

The stress tensor  $\sigma$  (X) is related to the gradient of displacements by the following equation

$$\sigma_{ij} = \lambda U_{k,k} \delta_{ij} + \mu (U_{i,j} + U_{j,i})$$
(1)

where the comma denotes partial differentiation and  $\lambda$  and  $\mu$  are the Lame's constants.

Balance of linear momentum yields the following equation of motion written in terms of displacement gradients.

$$\mu U_{i,jj} + (\lambda + \mu) U_{j,ii} + \rho U = f_{i}$$
(2)

where  $\rho$  is the mass density and f are the components of the body force per unit volume.

Solution of the equations of motion (2) must satisfy appropriate boundary conditions. The displacement boundary value problem assumes a knowledge of displacements on the entire surface S.

$$\mathbf{U}_{\mathbf{f}}\left(\mathbf{X}\right) = \overline{\mathbf{U}}_{\mathbf{f}}\left(\mathbf{X}\right) \tag{3}$$

when X denotes the orthogonal coordinates  $X_1$ ,  $X_2$ ,  $X_3$  and  $\overline{U}_1$  are known values of the surface displacements. The traction boundary value problem is

$$t_{i}(X) = \sigma \quad n = \tilde{t}_{i}(X)$$
(4)

when the vector function  $\overline{t}_i(X)$  is prescribed for XES. Unit vector n, is the outward normal vector for the body P.

As an initial approximation to the local response of an elastic body to an ultrasonic wave, consider a plane displacement wave propagating with phase velocity C in a direction described by a propagation vector  $\vec{p}$  as [13].

$$\vec{U} = A \vec{d} e^{i\eta}$$
 (5)

where

$$\eta = K(\vec{X} \cdot \vec{p} - ct)$$

Equation (5) describes a plane harmonic wave with  $\vec{x} \cdot \vec{P} = \text{constant}$  describing a plane normal to the propagation vector  $\vec{p}$ .

Two types of plane harmonic waves described by Equation (5) exist which are solutions to Equation (2). Waves of the type where  $d = \frac{1}{2}$  are called

)ongitudinal waves and the phase velocity is denoted as  $C_L$ . Waves of this type, where  $\vec{d} \cdot \vec{p} = 0$ , are called transverse waves, and the phase velocity for this type of wave is denoted as  $C_T$ .

Substitution of Equation (5) into Equation (1) yields the following form for the components of the stress tensor.

$$\sigma_{ij} = \left[\lambda \delta i j (d_{\ell} p_{\ell}) + \mu (d_{i} p_{j} + d_{j} p_{i})\right] i k A e^{i\eta}$$
(6)

when the summation convention is employed.

The presence of a subsurface layer or disconunity generally produces a change in the wave propagating in a medium. Acoustical speckle interferometry utilizes the reflection, refraction, and mode conversion of incident elastic waves at the interface of two elastic media as a basic description of the transmission and reflection of elastic waves. Consider initially two joined elastic half-spaces, as illustrated in Figure 1. An incident longitudinal wave, denoted as a p-wave, is incident on the boundary of the two elastic half-spaces. At the interface, boundary conditions and conditions of continuity will result in both reflection and refraction of longitudinal and transverse waves from an incident p-wave. The notation and description of the waves will be the same as described in reference [13] and repeated here for completeness of discussion. Unit propagation vectors are illustrated in Figure 1, with material properties of the incident medium denoted as  $\lambda,\,\rho,\,\mu.$ Material properties of the refracted medium are labeled  $\lambda^B$ ,  $\mu^B$ ,  $\rho^B$ . Superscripts,  $p^n$ , on the propagation vectors are used to describe the reflected and refracted waves as given in the following equations.

## Incident Longitudinal wave (p-wave), n = 0.

The incident P-wave will be described by the unit propagation vector  $\overrightarrow{p}^{\diamond o}$ , when

$$p^{o} = \cos \theta_{o} \vec{i}_{1} + \sin \theta_{o} \vec{i}_{2}$$
 (7-a)

Displacement vector is described as  $\overrightarrow{d}^{\circ} = \overrightarrow{p}^{\circ}$ ; therefore

$$\vec{U}^{0} = \mathbf{A}_{0} \left[ \cos \theta \quad \vec{i}_{1} + \sin \theta_{0} \vec{i}_{2} \right] e^{i \eta_{0}}$$
(7-b)

and

$$\eta = K_{o} \left[ X_{1} \cos \theta_{o} + X_{2} \sin \theta_{o} - C_{o} t \right]$$
(7-c)

Stress components for the incident p-wave are calculated from Equation (6) and are

$$\tau_{21}^{0} = ik_{0} \left(\lambda + 2\mu \cos^{2}\theta_{0}\right) A_{0} e^{i\eta_{0}}$$
(8-a)





$$\tau_{22}^{0} = 2ik_{0} \mu \sin \Theta \cos \Theta A_{0} e^{i\eta_{0}}$$
(8-b)

# Reflected longitudinal wave, n = 1.

The reflected p-wave is described by the unit propagation vector as

$$\vec{p}^1 = \sin \Theta_1 \vec{i}_1 - \cos \Theta_1 \vec{i}_2$$
 (9-a)

Displacement vector is  $\vec{d}^1 = \vec{p}^1$ 

$$\vec{U}^{1} = A_{1} \left[ \sin \Theta_{1} \vec{i}_{1} - \cos \Theta_{1} \vec{i}_{2} \right] e^{i\eta_{1}}$$
(9-b)

vhere

$$\eta_1 = k_1 \left[ X_1 \sin \Theta_1 - X_2 \cos \Theta_1 - C_1 t \right]$$
(9-c)

Stresses for this wave are

$$\tau_{21}^{1} = ik_{o} \mu \sin 2\theta_{1} A_{1} e^{i\eta_{1}}$$
 (10-a)

$$\tau_{22}^{1} = \mathbf{i} \ \mathbf{k}_{1} \left[ \lambda + 2\mu \ \cos^{2} \Theta_{1} \right] \mathbf{A}_{1} \ \mathbf{e}^{\mathbf{i} \eta_{1}}$$
(10-b)

Reflected transverse wave (sv-wave), 
$$n = 2$$
.

Propagation vector, displacement vector and stress components are given by the following equations.

$$\vec{p}^2 = \sin \Theta_2 \vec{i}_1 - \cos \Theta_2 \vec{i}_2$$
(11-a)

The description of a transverse vertical wave is given by  $\vec{d}_2 = \vec{i}_3 + \vec{p}_2$ , which yields the following form for the displacement vector.

$$\vec{U}^2 = A_2 \left[ \cos \theta_2 \vec{i}_1 - \sin \theta_2 \vec{i}_2 \right] e^{i\eta_2}$$
(11-b)

$$\eta_2 = k_2 \left[ X_1 \sin \Theta_1 - X_2 \cos \Theta_2 - C_2 t \right]$$
(11-c)

$$\tau_{21}^{2} = -\frac{ik_{0}C_{L}^{\mu}}{C_{T}}\cos 2\theta_{2}A_{2}e^{i\eta_{2}}$$
(12-a)

$$\tau_{22}^{2} = -ik_{2}\mu \sin 2\Theta_{2}A_{2}e^{i\eta_{2}}$$
 (12-b)

Refracted longitudinal wave, n = 3.

$$\vec{p}^3 = \sin \Theta^3 \vec{i}_1 + \cos \Theta_3 \vec{i}_2$$
 (13-a)

$$\vec{U}^3 = A_3 \left[ \sin \theta_3 \vec{i}_1 + \cos \theta_3 \vec{i}_2 \right] e^{i\eta_3}$$
 (13-b)

$$n_3 = K_5 \left[ X_1 \sin \theta_3 + \cos \theta_3 - C_3 t \right]$$
(13-c)

$$\tau_{21}^{3} = \frac{iK_{O}C_{L}}{C_{Y}^{B}} \mu B \sin 2\Theta_{3}A_{3} e^{in_{3}}$$
(14-a)

$$\tau_{22}^{3} = ik_{3} \left[ \lambda^{B} + 2\mu^{B} \cos^{2} \Theta_{3} \right] A_{3} e^{in_{3}}$$
 (14-b)

## Refracted transverse wave, n = 4.

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The transverse vertical wave in the refracted medium is described by  $\vec{d}^3 = \vec{i}_3 X p$  where

$$\vec{p}^{4} = \sin \Theta_{4} \vec{i}_{1} + \cos \Theta_{4} \vec{i}_{2}$$
 (15-a)

$$\vec{U}^{4} = A_{4} \left[ -\cos \Theta_{4} \vec{i}_{1} + \sin \Theta_{4} \vec{i}_{2} \right] e^{i\eta_{4}}$$
(15-b)

$$n_{4} = K_{4} \left[ X_{1} \sin \Theta_{4} + X_{2} \cos \Theta_{4} - C_{4} t \right]$$
 (15-c)

$$\tau_{21}^{4} = iK_{4}\mu^{B}\cos 2\Theta_{4}A_{4}e^{i\eta_{4}}$$
 (16-a)

$$\tau_{22}^{4} = iK_{4}\mu^{B} \sin 2\theta_{4}A_{4}e^{i\eta_{4}}$$
 (16-b)

At the interface, a condition of perfect contact will be assumed and the displacement and traction vector at the interface  $X_2 \approx 0$  must be continuous for all  $X_1$  and t.

$$\vec{U}^0 + \vec{U}^1 + \vec{U}^2 = \vec{U}^3 + \vec{U}^4$$
 (17-a)

$$t^0 + t^1 + t^2 = t^3 + t^4$$
 (17-b)

These equations written in component notation are

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$$U_{i}^{0} + U_{i}^{1} + U_{i}^{2} = U_{i}^{3} + U_{i}^{4}$$
(18-a)

$$\tau_{2_{i}}^{1} + \tau_{2_{i}}^{1} + \tau_{2_{i}}^{2} = \tau_{2_{i}}^{3} + \tau_{2_{i}}^{4}$$
  $i = 1, 2$  (18-b)

Equations (7-c, 9-c, 11-c, 13-c) require that boundary conditions are satisfied for all  $X_1$  and t yields the following.

$$K_0 \sin \Theta_0 = K_1 \sin \Theta_1 = K_2 \sin \Theta_2 = K_3 \sin \Theta_3$$

$$= K_4 \sin \Theta_4 \tag{19-a}$$

$$K_0 C_L = K_1 C_L = K_2 C_T = K_3 C_L^B = K_4 C_T^B$$
 (19-b)

Equations (17-a) and (7-b, 9-b, 11-b, 13-b) yield the following conditions on continuity of displacements at the interface.

$$A_0 \sin \Theta_0 + A_1 \sin \Theta_1 + A_2 \cos \Theta_2$$
  
=  $A_3 \sin \Theta_3 - A_4 \cos \Theta_4$  (20)  
$$A_0 \cos \Theta_0 - A_1 \cos \Theta_1 + A_2 \sin \Theta_2$$
  
=  $A_3 \cos \Theta_3 + A_4 \sin \Theta_4$  (21)

Equation (18-b), coupled with Equations (8, 10, 12, 14), yield the following conditions for conditions on the components of the stress tensor at the interface.

$$\mu A_{0} \sin 2\Theta_{0} - \mu A_{1} \sin 2\Theta_{1} - \mu A_{2} \frac{CL}{CT} \cos 2\Theta_{2}$$

$$= \frac{C_{L}}{C_{L}^{B}} \mu^{B} A_{3} \sin 2\Theta_{3} - A_{4} \frac{C_{L}}{C_{T}^{B}} \mu^{B} \cos 2\Theta_{4} \qquad (22)$$

$$K_{0} \left[\lambda + 2\mu \cos^{2} \Theta_{0}\right] A_{0} + K_{1} \left[\lambda + 2\mu \cos^{2} \Theta_{1}\right] A_{1}$$

$$- K_{2}\mu \sin 2\Theta_{2}A_{2} = K_{3} \left[\lambda^{B} + 2\mu^{B} \cos^{2}\Theta_{3}\right] A_{3}$$

$$+ K_{4}\mu^{B} \sin 2\Theta_{4}A_{4} \qquad (23)$$

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Equations (20-23) can be put in a matrix form amenable to computation for a system of n layered media.

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} X \end{bmatrix} = \begin{bmatrix} B \end{bmatrix}$$

(24)

where

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} -\sin\theta_1 & -\cos\theta_2 & \sin\theta_3 & -\cos\theta_4 \\ \cos\theta_1 & -\sin\theta_2 & \cos\theta_3 & \sin\theta_4 \\ \\ \mu\sin2\theta_1 & \mu \frac{c}{c_T} \cos2\theta_2 & \frac{c}{c_L} \frac{1}{B} \mu^B \sin2\theta_3 & -\frac{c}{c_T} \frac{1}{B} \mu^B \cos2\theta_4 \\ \\ -(\lambda + 2\mu \cos^2\theta_1) & \frac{c}{c_T} \mu \sin2\theta_2 & \frac{c}{c_L} \frac{1}{B} \lambda^B + 2\mu^B \cos^2\theta_3 & \frac{c}{c_T} \frac{1}{B} \mu^B \sin2\theta_4 \end{bmatrix}$$
$$\begin{bmatrix} X \end{bmatrix} = \begin{bmatrix} A_1 / A_0 \\ A_2 / A_0 \\ A_3 / A_0 \\ A_4 / A_0 \end{bmatrix}$$
$$\begin{bmatrix} B \end{bmatrix} = \begin{bmatrix} \sin \theta_0 \\ \cos \theta_0 \\ \mu \sin 2\theta_0 \\ \lambda + 2\mu \cos\theta_0 \end{bmatrix}$$

Equation (24) forms the solution for the amplitude ratios  $Ai/A_0$  for the reflection and refraction of an incident p-wave of two perfectly joined half-spaces. For a system of n-layers, Equations (19) and (24) can be utilized to determine the propagation and energy partition at the boundary of each layer.

Some special cases of the interfaces are of primary importance for problems in acoustical speckle interferometry. A liquid-solid boundary usually forms the initial interface, and a solid-liquid boundary forms the last boundary interface for a solid immersed in a liquid. In addition, a subsurface layer from a practical point forms a boundary of an elastic body with air, which is the condition of a subsurface void. At this interface, the refraction of elastic waves will be neglected; therefore, only the reflection of elastic waves at a free surface will be considered. Since these special cases are of particular importance in acoustical interferometry, they will be examined in some detail.

## A. Liquid-Solid Boundary

Suppose that the medium comprised of the incident p-wave is liquid and the refracting medium is an elastic solid. For this condition, the reflected SV-wave is zero; therefore, the boundary conditions reduce to the following form.

$$U_{i}^{0} + U_{i}^{1} = U_{i}^{3} + U_{i}^{4} \qquad (i = 1, 2)$$
(25)

$$\tau_{22}^{0} + \tau_{22}^{1} = \tau_{22}^{3} + \tau_{22}^{4}$$
(26)  
$$\tau_{21}^{3} + \tau_{21}^{4} = 0$$

Equations (25) and (26) are solved for the amplitude ratios Ai/A0, and are displayed in matrix form for computation.

$$\begin{bmatrix} -\sin \Theta_{1} & \sin \Theta_{3} & -\cos \Theta_{4} \\ \cos \Theta_{1} & \cos \Theta_{3} & \sin \Theta_{4} \\ -\lambda & \frac{C_{L}}{C_{L}^{B}} \begin{bmatrix} \lambda^{B} + 2\mu^{B}\cos^{2}\Theta_{3} \end{bmatrix} \frac{C_{L}}{C_{L}^{B}} \mu^{B}\sin 2\Theta_{4} \end{bmatrix} \begin{bmatrix} A_{1}/A_{0} \\ A_{3}/A_{0} \\ A_{4}/A_{0} \end{bmatrix} = \begin{bmatrix} \sin \Theta_{0} \\ \cos \Theta_{0} \\ \lambda \end{bmatrix} (27)$$

## B. Solid-Liquid Boundary

The boundary between the two layers is comprised of an elastic solid reflecting medium and a liquid refracting medium. The p-wave  $(p^0)$  represents the incident wave and the transmitted sv-wave is zero. Boundary conditions reduce to the following.

$$U_{i}^{0} + U_{i}^{1} + U_{i}^{2} = U_{i}^{4}$$
 (1 = 1,2) (28)

$$\tau_{22}^{0} + \tau_{22}^{1} + \tau_{22}^{2} = \tau_{22}^{4}$$
(29)

$$\tau_{21}^{0} + \tau_{21}^{1} + \tau_{21}^{2} = 0$$
 (30)

Equations (28, 29) are solved, and in matrix notations are written in terms of Ai/A0 as

$$\begin{bmatrix} -\sin \theta_{1} & -\cos \theta_{2} & \sin \theta_{3} \\ \cos \theta_{1} & -\sin \theta_{2} & \cos \theta_{3} \\ [\lambda + 2\mu\cos^{2}\theta_{1}] & \frac{C_{L}}{C_{T}}\mu\sin^{2}\theta_{2} & \frac{C_{L}}{C_{L}}B \\ \end{bmatrix} \begin{pmatrix} A_{1}/A_{0} \\ A_{2}/A_{0} \\ A_{3}/A_{0} \end{bmatrix} = \begin{bmatrix} \sin \theta_{0} \\ \cos \theta_{0} \\ \lambda + 2\mu\cos^{2}\theta_{0} \end{bmatrix}$$
(31)

## C. Free Boundary

At a free surface, the following boundary conditions are satisfied for the stress components.

$$\tau_{2_{i}}^{0} + \tau_{2_{i}}^{1} + \tau_{2_{i}}^{2} = 0 \qquad i = 1,2 \qquad (32)$$

Solution of Equation (32) in terms of the amplitude ratios are [13]

$$\frac{A_1}{A_0} = \frac{\sin 2\theta_0 \sin 2\theta_2 - K^2 \cos^2 2\theta_2}{\sin 2\theta_0 \sin 2\theta_2 + K^2 \cos^2 2\theta_2}$$
(33-a)

$$\frac{A_1}{A_0} = \frac{2K \sin 2\theta_0 \cos 2\theta_2}{\sin 2\theta_0 \sin 2\theta_2 + K^2 \cos^2 2\theta_2}$$
(33-b)

where

$$K = \left[\frac{2(1-\nu)}{1-2\nu}\right]^{\frac{1}{2}}$$

## III. NUMERICAL RESULTS

The numerical solution for a layered elastic half space immersed in a liquid medium involves the solution of Equations (24), (27), and (31) for the amplitude ratios  $A_1/A_0$ ,  $A_2/A_0$ ,  $A_3/A_0$ , and  $A_4/A_0$ . Equation (27) is utilized to determine the amplitude ratios at a liquid-solid boundary for an incident p-wave in the liquid. At each solid boundary, Equation (24) is used to calculate the amplitude ratios. At the solid-liquid boundar , amplitude ratios are calculated by Equation (31). Thus, for a multiple-layered medium, these equations are repeatedly applied for the number of interfaces.

As an illustration of the liquid-solid boundary equation, consider an incident p-wave in water at a steel interface for various angles of incidence  $\Theta_0$ . As expected, an incident p-wave gives rise to a reflected p-wave and transmitted p-waves and sv-waves in the solid. Equation (27) was solved numerically for the following data.

| λ | steel | = | 16.42 × 10 <sup>6</sup> psi |
|---|-------|---|-----------------------------|
| ρ | steel | # | 0.284 lbm/in <sup>3</sup>   |
| μ | steel | = | 11.6 × 10 <sup>6</sup> psi  |
| β | water | = | 0.318 × 10 <sup>6</sup> psi |
| ρ | water | = | 0.0361 1bm/in <sup>3</sup>  |

Amplitude ratios for various values of the incident angle  $\Theta_0$  are given in Figure 2.

An incident p-wave in a solid at a water interface gives rise to both reflected p-waves and sv-waves and a transmitted p-wave. Equation (31) is used to calculate the amplitude ratios at this boundary and in Figure 3 the amplitude ratios are shown versus the angle of incidence  $\Theta_0$ .

A solid elastic half space for an incident p-wave in one solid gives rise to both reflected and refracted p-waves and sv-waves in each solid. The amplitude ratios for this boundary are calculated from Equation (24). As an illustration of this solution procedure an incident p-wave in steel at a steel aluminum boundary is used as data for the calculation of the amplitude ratios for various angles of incidence  $\Theta_0$ . Data for the aluminum are shown in Figure 4.

> $\lambda$  Aluminum = 7.42 × 10<sup>6</sup> psi  $\mu$  Aluminum = 4.00 × 10<sup>6</sup> psi

 $\rho$  Aluminum = 0.100 lbm/in<sup>3</sup>

An example problem of a two-layered elastic half space immersed in water is chosen to illustrate the solution procedure for the layered medium problem. Geometry for this example is show. in Figure 5, and only reflected and refracted p-waves at each interface are shown in this illustration; however, sv-waves exist at each solid boundary. The particular significance of the p-waves is in the application of acoustical speckle interferometry to object motion measurements in layered media. Reference [12] illustrates that the p-waves are amenable to object motion measurement; therefore, this discussion will be restricted to p-wave propagation. Consider an incident p-wave in water at interface 1 which is a liquid-solid boundary. Solid 1 is taken to be steel with the same properties for the liquid-solid example. Superscripts refer to the particular wave component, as discussed in the previous section, and subscripts refer to each boundary. A transmitted p-wave at boundary, I will become an incident p-wave at boundary 2 and incident angle  $\Theta_2^{\vee} = \Theta_1^{\vee}$ . For the two-layer elastic half space, the incident waves at each boundary are listed in the following:

> Boundary 1:  $\overrightarrow{p}_1^0 = \overrightarrow{p}^0$ ,  $\Theta_1^0 = \Theta^0$ Boundary 2:  $\overrightarrow{p}_2^0 = \overrightarrow{p}_1^3$ ,  $\Theta_2^0 = \Theta_1^3$



# Figure 2. Amplitude ratio of a water steel interface for an incident p-wave in water.



Figure 3. Amplitude ratio of a steel water interface for an incident p-wave in steel.

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2.178



Figure 4. Amplitude ratio of an aluminum steel elastic half space for an incident p-wave in aluminum.



Figure 5. Reflection and refraction of p-waves in a layered medium for an incident p-wave in the liquid medium.

Boundary 3:  $\overrightarrow{p}_3^0 = \overrightarrow{p}_2^1$ ,  $\Theta_3^0 = \Theta_2^0$ Boundary 4:  $\overrightarrow{P_4} = \overrightarrow{P_2}^3$ ,  $\overrightarrow{O_4} = \overrightarrow{O_2}^3$ Boundary 5:  $\vec{P}_0^5 = \vec{P}_4^1$ ,  $\Theta_5^1 = \Theta_4^1$ Boundary 6:  $\overrightarrow{P}_6^0 = \overrightarrow{P}_5^3$ ,  $\Theta_6^0 = \Theta_5^3$ 

Amplitude ratios at each interface for an initial incidence angle  $\theta^0 = 0^0$ are listed in the following for the two-layer elastic half space. The computer program for these calculations is listed in Appendix A.

> Liquid-Solid 1 Boundary 1  $A_1/A_0 = 0.93810$  $A_3/A_0 = 0.061905$  $A_4/A_0 = 0.00$ Solid 1-Solid 2 Boundary 2  $A_1/A_0 = -0.45965$  $A_2/A_0 = 0.00$  $A_3/A_0 = 1.4597$  $A_4/A_0 = 0.00$ Solid 1-Liquid Boundary 3  $A_1/A_0 = -0.93809$  $A_2/A_0 = 0.00$  $A_3/A_0 = 1.9381$ Solid 2-Liquid Boundary 4  $A_1/A_0 = -0.8411$  $A_2/A_0 = 0.00$  $A_3/A_0 = 1.8411$ Solid 2-Solid 1 Boundary 5  $A_1/A_0 =$ 0.45965  $A_2/A_0 = 0.00$  $A_3/A_0 = 0.54035$  $A_{\rm L}/A_{\rm O} = 0.00$ Solid 1-Liquid Boundary 6  $A_1/A_0 = -0.93809$  $A_2/A_0 = 0.00$  $A_2/A_0 = 1.9381$ 20

Amplitude ratios at each interface for an initial incidence angle  $\Theta^0 = 20^0$  are listed as follows:

Liquid-Solid Boundary 1  $A_1/A_0 = 0.92684$  $A_3/A_0 = 0.17302$  $A_4/A_0 = 0.65243$ Solid 1-Solid 1 Boundary 2  $A_1/A_0 = 0.44433$  $A_2/A_0 = 0.09316$  $A_3/A_0 = 1.4611$  $A_4/A_0 = 0.017700$ Solid 1- Liquid Boundary 3  $A_1/A_0 = 0.81650$  $A_2/A_0 = 0.69193$  $A_3/A_0 = 2.0430$ Solid 2- Liquid Boundary 4  $A_1/A_0 = 0.72645$  $A_2/A_0 = 0.65056$  $A_3/A_0 = 1.9423$ Solid 2- Solid 1 Boundary 5  $A_1/A_0 = 0.44651$  $A_2/A_0 = 0.08059$  $A_3/A_0 = 0.53946$  $A_4/A_0 = 0.0077461$ 

Solid 1- Liquid Boundary 6

| $A_1/A_0$ | = | -0.81650 |
|-----------|---|----------|
| $A_2/A_0$ | = | 0.69193  |
| A3/A0     | = | 0.02430  |

### IV. ACOUSTICAL SPECKLE INTERFEROMETRY

As a tool of quantitative nondestructive testing of materials, the spectral analysis of ultrasonic pulses in elastic solids has attracted wide attention in recent years. Krautkrämer [14] suggested in 1959 that measurement of the pulse shape could be used to determine the size and orientation of flaws in materials. Methods for determining the spectral content of broad-band ultrasonic pulses reflected and scattered in materials were subsequently developed by Gericke [15]. In his pioneering work, he showed that

the spectral content of pulses propagating in steel specimens was greatly dependent on the material's microstructure. In later work [16], he investigated the spectral content of echoes from cylindrical cavities oriented perpendicular and parallel to the direction of wave propagation. From these experiments he concluded that it might be feasible to use ultrasonic-spectroscopy measurements in conjunction with normal pulse-echo techniques to determine not only the location of a defect, but also its shape. Brown [17]has reviewed some results obtained by Lloyd [18] on the spectral response of various conical and flat-topped cylinders, which could be explained qualitatively in terms of the cylinder's dimensions and geometry. Sachse [19] has reported an experimental investigation of the spectral analysis of wideband ultrasonic pulses as scattered by a circular, cylindrical, fluid-filled cavity in an elastic solid. It was shown that either the diameter of the cavity or the wave speed of the fluid can be determined from the time record of the scattered pulses. Furthermore, an empirical formula was developed to relate the diameter and the wave speed to the intervals between the minima or maxima of the power spectra. The author concluded that the method of ultrasonic spectroscopy which are originated by Gerick can be used to detect the dimensions and mechanical properties of flaws and impurities inside elastic solids.

Theories of the scattering of acoustic waves have been extensively devleoped since the fundamental work of Lord Rayleigh [20]. A review of the existing theories as well as some numerical results of scattered waves in elastic solids have been published in the monograph by Pao and Mow [21]. The case of a circular, cylindrical cavity inside an elastic solid was investigated in detail by White [22]. He measured amplitudes and arrival times of plane harmonic waves with long duration, using standard ultrasonic techniques. His measured angular distributions of the scattered wave amplitudes for both incident longitudinal and shear waves agreed very well with his theoretical analysis.

The interaction of sound waves and pulses with solid cylinders immersed in a fluid has been of interest in underwater acoustics for some time. Most extensively studied has been the scattering of pulses incident normal to the axis of the cylinder. In 1967, Goodman, Bunney, and Marshall [23] reported the existence of a Rayleigh-type circumferential wave propagating around a solid cylinder. Later, Neubauer 24-26 reported the results of experiments in which pulses were used to study the propagation of the circumferential waves on aluminum cylinders immersed in water. In 1969, Bunney, Goodman, and Marshall [27] also reported observation of the Rayleigh-type wave. Several experiments of the scattering of broad-band ultrasonic pulses by cylindrical inclusions in elastic solids have been performed by Sachse and Chian [28] and Bifulco and Sachse [29]. The inclusions were fluids or solids whose wave speed was less than that of the solid matrix material. It was shown that in a non-destructive testing application, the size and wave speed of the inclusion could be determined from measurements of the arrival times of various scattered pulses. In a recent work [30] measurements are reported of the arrival times of broad-band ultrasonic pulses scattered by a circular, cylindrical solid inclusion imbedded in a matrix whose longitudinal wave speed is lower than that of the scatter.

In many instances in practice, it is highly desirable to obtain an accurate and rapid measure of the stress in a structural member. Ultrasonics

offers a great tool for the realization of a system capable of performing this task. Ultrasonic-pulse spectroscopy measurements has been used to measure the stress-induced interference effects between two shear waves propagating in uniaxially deformed specimens of aluminum [31]. This technique shows considerable promise as a means for measuring and monitoring the applied stresses in materials.

Ensminger [32] documents many modern applications dealing with topics such as thickness measurements, inspection of metals and non-metals and the determination of bond integrity. Ultrasonic inspection is further being extended to tissue examinations and bone scans in the medical field [33].

As an experimental nor destructive stress analysis, the polarized transverse ultrasonic waves have provided a new method of measurements which is christened the acoustoelasticity. Similar to the photoelastic effect, the velocity of the transverse soundwaves traversing a stressed elastic solid is not a constant as it would be in an isotropic solid. The velocity depends on the direction of the particle motion (polarization), the direction of wave propagation, and the state of stress. With the recent advancement of ultrasonic techniques, one can generate, transmit and detect plane polarized ultrasounds. Therefore, stress-induced acoustical birefringence can be measured. As in photoelasticity, the difference of propagation velocities in shear waves polarized in principal stress directions is proportional to the principalstress differences in the plane-stress state. Thus, this technique is a nondestructive test method and determines stresses by ultrasonic shear waves which do not require a transparent plastic model [34-36].

Plastic deformation in crystalline solids by means of high-frequency stress wave propagations has been studied by a number of investigators [37,38]. The study of the relation between the propagation of ultrasonic waves and plastic deformation in single crystals has been discussed in detail. Specifically, changes in attenuation and velocity of ultrasonic waves have been measured as a function of plastic strain during the deformation process. These techniques have also been applied to the investigation of some aspects of strain hardening mechanisms [39].

Knowledge and control of the transmission and reflection of ultrasonic waves in layered media is an important basic problem in underwater acoustics. The problem of transmission of sound at oblique incident angles through a solid multilayer system of plane parallel plates was treated by Thompson [40], Brekhovskikh [41], and others. The most detailed solution of the multilayer problem is by Shaw and Bug1 [42], whose theoretical approach was directed toward the investigation of conditions under which interface waves may be generated. In a recent work [43], the wave equation was solved to determine the transmission and reflection coefficients for plane waves at oblique incidence on a system of n layers of plane parallel plates.

Acoustic holography is the newest branch in acousting imaging technology. It is directly comparable with optical holography in the phenomenological sense, because to make a hologram it is necessary that the two beams of radiation used have the ability to interfere with one another. Acoustic holography underwent very rapid development during the last few years, and simulated the general field of acoustic imaging through the introduction of novel techniques for visualizing acoustic excitation. In contrast to optical holography, which has sometimes been described as a solution looking for a problem, acoustical holography was from the outset developed for a specific purpose. This purpose is that of all acoustical probing systems, namely, detecting, locating, and imaging a structure immersed in a medium opaque to electromagnetic radiation. This description encompasses a variety of specific problems, such as nondestructive testing, medical imaging, oil exploration, and underwater imaging.

A recent development in laser technology, referred to as speckle interferometry, has provided for a new technique in experimental mechanics to measure surface displacements of deformed solids. Basically this method records the laser intensity variation across the surface of an object due to the random interference of the microscopic character of the illuminated surface. Figure 6 illustrates the basic method for recording a double exposure laser speckle photograph. A high resolution photographic film records the granular pattern on the film plane of a camera. If the object is displaced from a reference configuration, the speckles are mapped to a new location on the film plane corresponding to the object motion. Data analysis consists of pointwise filtering as illustrated schematically in Figure 7. This method of data analysis assumes a constant value of displacement within the small area of illumination, and the resulting interference pattern is obtained by taking optically the Fourier transform of the amplitude transmission function of the photographic transparency. Interference fringes are therefore a direct measure of local object motion within the area of illumination. The discrete global response of the body is obtained by pointwire filtering of many small areas of the photograph transparency.

Because the speckle effect is statistical in nature and the basic concepts occur in many areas of physics and engineering, the previously developed techniques in optics suggest a parallel development in ultrasonics. In a recent work [11,12] a basic theory of one-dimensional pulse-echo and continuous wave acoustical speckle interferometry was developed. This method utilized the statistical concepts of speckle and one-dimensional correlation of reference and displaced signals to determine object motion of subsurface scattering layers. This study established the feasibility of the acoustical speckle concept for object motion measurements.

## V. BASIC THEORY OF DISPLACEMENT MEASUREMENTS UTILIZING ULTRASONICS

This section presents the geometrical concepts of displacement functions of a continuum and the correlation of a reference and deformed ultrasonic signal as a measure of object motion. The basic problem may be described in the following way: given the measured ultrasonic global response of signals before and after deformation, it is then required to calculate the local object displacement vector from the global reference and deformed configurations of a body. Thus the basic problem is geometrical in nature and initially is not concerned with the external forces necessary to cause the geometrical deformation.

Let the position of the points in a continuum in the initial (unstrained state) be given with respect of the coordinates  $X_1$ ,  $X_2$ ,  $X_3$ , as illustrated in Figure 8. The body is deformed with respect to the unstrained coordinates and points are displaced to new coordinates denoted as  $X_1$ ,  $X_2$ ,  $X_3$  (Figure 8).



ROUGH SURFACE





Figure 7. Data analysis for pointwise filtering in in-plane measurements.



Figure 8. Displacement components of a deformed body.

The coordinates of an arbitrary point in the deformed configuration are expressed in terms of the original coordinates by the following equation.

$$X'_{i} = X_{i} + U_{i}(X_{1}, X_{2}, X_{3}, t)$$
 (34)

where U<sub>1</sub> are called displacement components and are taken to be continuous functions of the original coordinates  $X_1$ ,  $X_2$ ,  $X_3$ . Thus, in general, the displacement functions vary from point to point in a deformed body.

Suppose a continuous mode or pulse echo ultrasonic scan is made of a rough scattering surface with reference area M as illustrated in Figure 9. The field reflected from the scattering surface at the plane of the receiving transducer in a plane immediately adjacent to that surface is described by a complex function  $\alpha(\xi,n)$ , which represents a reflected p-wave or SV-wave from an incident p-wave in an elastic solid. The complex field P(X) where  $X = (X_1, X_2)$  denotes the ordered pair of numbers in the plane of the receiving transducer which is parallel to  $(\xi,n)$  and represents the amplitude of the reference signal, which is the field of interest from the acoustical signal. Details of both pulse echo and continuous mode scanning techniques of scattering surfaces are described in reference [11,12].

Now suppose that the receiving transducer is returned to the original position and the scattering surface is displaced from its reference configuration. A complex field P(X') represents the amplitude of the received signal where the coordinates  $X' = X_1, X_2$  are parallel to the plane  $(\xi, \eta)$ . If the displacements functions in Equation (34) are substituted into the representation of the displaced signal, the special form reduces to the following:

$$P(X^{\prime}) = P(X_1 + U_1, X_2 + U_2)$$
(35)

where the received signal is assumed to be a function of the coordinates parallel to the plane of the scattering surface. The reference and displaced signals are illustrated in Figure 10.

The problem now becomes one of correlating the signals P(X) and P(X') to measure the local displacement components  $U_1$  and  $U_2$ . The basis for this measurement is the autocorrelation function of the two signals which is given in the following equation:

$$C(U_1, U_2) = \int P(X_1, X_2) P(X_1 + U_1, X_2 + U_2) dX_1 dX_2$$
(36)  
M

The one-dimensional correlation of continuous mode scanning for a rigid deformation is discussed in reference [12]. This study demonstrated that Equation (36) forms the basic concept for object motion measurement of subsurface acoustic scattering layers which agrees with the statistical relationships in laser speckle interferometry.

Although Equation (36) has been demonstrated to be a measure of object motion, some limitations are imposed on the applications because the





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Figure 10. Reference and deformed surface for correlation of acoustical signals.

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displacement functions  $U_1$  and  $U_2$  are, in general, continuous functions of the initial coordinates  $(X_1, X_2)$  and are the unknown quantities to be determined. If the displaced surface is just a uniform translation in the  $X_1, X_2$  directions, then  $U_1, U_2$  are constant and the application of Equation (36) is straightforward; however, in the presence of a deformed surface,  $U_1$  and  $U_2$  cannot be interpreted in terms of a global uniform translation. The basic approach used in computing the correlation of P(X) and P(X') is to assume the basic theory of data analysis in pointwise filtering used in single beam laser speckle interferometry (Figure 11). Object motion displacements are obtained by passing a laser beam through a small area of a double exposed transparency which contains both the reference and deformed images. Interference fringes are observed as intensity of the light amplitude in the transform plane. This analysis utilizes the shift theorem which restricts the displacement components to be constant within the area of illumination. Practical applications for a He-Ne laser restricts the area to be a circular region approximately 2 mm in diameter.

This restriction in optics suggests the following approach in acoustical speckle interferometry. Let the reference scan be recorded over some reference area M in the  $X_1, X_2$  plane, as illustrated in Figure 11. Suppose that within scme small neighborhood of a point  $P_{o} \in P(X_{o})$  the displacement is assumed to be uniform. The acoustical signal corresponds to a small neighborhood of the point  $P_{o} \in P(X_{o})$ . Therefore the Equation (36) can now be used in the form

$$\Delta C(U_1, U_2) = \int \Delta P(X_1, X_2) \Delta P(X_1 + U_1, X_2 + U_2) dX_1 dX_2$$
(37)  
M

where  $\Delta P(X)$  and  $\Delta P(X')$  correspond to a small surface surrounding the points of interest. The correct values of  $U_1, U_2$  corresponding to the object motion displacement will result in a maximum value of the correlation function  $\Delta C(U_1, U_2)$ . This correlation procedure corresponds to the data analysis at pointwise filtering in optics and thus completes the analysis of the displacement of a point. The procedure to determine the discrete displacement values will follow the procedure in optics as discussed in reference [7].

A discussion of the cross-correlation peak should include the effects of deformation on the local accuracy of the correlation function. This problem in local deformation of an object is similar to the problem of image correlation with geometric distortion on the accuracy of image restoration [44]. Basically, the image restoration is investigated for distortions represented by an affine transformation of image coordinates, which is an offset plus scaling and rotation of each image coordinate axis [45-47]. The image analysis assumes a fixed geometric distortion and then a proper choice of integration area in the cross-correlation can be optimized for minimum local error. Geometric distortion for deformable bodies is generally unknown; therefore, this represents the inverse problem to image registration. A discussion of this problem will include the restrictions and assumptions in the linear theory of elasticity and an example problem will be chosen to illustrate the effects.

Let a point P be displaced to a point P', and point Q displaced to Q'. The displacement of point Q can be expanded in a linear Taylor's series as expressed in the following form.





$$\mathbf{U}_{1} \mid \mathbf{Q} = \mathbf{U}_{1} \mid \mathbf{P} + \frac{\partial U_{1}}{\partial \mathbf{X}_{1}} \Delta \mathbf{X}_{1} + \frac{\partial U_{1}}{\partial \mathbf{X}_{2}} \Delta \mathbf{X}_{2}$$
(38)

$$U_2 \mid Q = U_2 \mid P + \frac{\partial U_2}{\partial X_1} \Delta X_1 + \frac{\partial U_2}{\partial X_2} \Delta X_2$$

Equation (38) can be expressed in terms of the infinitesimal strains and rotation components which results in the following expression [48].

$$U_1 | Q = U_1 | P + \Delta U_1$$
 (39)  
 $U_2 | Q = U_2 | P + \Delta U_2$ 

where

$$\Delta U_1 = \varepsilon_{11} \Delta X_1 + (\varepsilon_{12} - \omega_3)$$

$$\Delta U_2 = (\varepsilon_{12} + \omega_3) \Delta X_1 + \varepsilon_{22} \Delta X_2$$

The correlation function can now be put in the following form.

$$\Delta C(U_{1} + \Delta U_{1}, U_{2} + \Delta U_{2}) = \int \Delta P(X_{1}, X_{2}) \Delta P(X_{1} + U_{1} + \Delta U_{1}, X_{2})$$

+ 
$$\Delta U_2$$
)  $d_{X_1} d_{X_2}$  (40)

Equation (40) has been demonstrated to be a measure of object motion, taking into consideration the restrictions and assumptions in the linear theory of elasticity; however, Equation (36) represents the general measure of object motion. In the presence of a largely deformed surface  $U_1$  and  $U_2$  can be interpreted in terms of a rigid body translation and rotation and normal and shear strains. Several numerical examples will be discussed in order to illustrate the application of numerical correlation in object motion measurements.

## VI. NUMERICAL EXAMPLES AND CONCLUSIONS

Several numerical examples will be discussed to illustrate the application of the numerical correlation in object motion measurements. A reference signal P(X) corresponding to the undeformed scan is illustrated in Figure 12. A line along the  $X_1$  axis is shown in Figure 13. The reference area M for all examples presented will comprise an array of  $100 \times 100$  data points. The displaced signal P(X') will be correlated with the reference signal for the specific cases of displacement components  $U_1$  and  $U_2$ . A correlation computer program is listed in Appendix B.

For a case of uniform translation in the absence of geometrical distortion, some simplifications in the integration area M allowed for a considerable reduction in computer time. The procedure utilized was to perform the correlation over two orthogonal lines of data points which comprise a length where object motion is assumed to be uniform. In the examples discussed, the five data points for this interval were used. Figure 14 is a graphical display of three examples of uniform translation. Figure 15 shows the surface P(X') for a uniform translation in the  $X_1, X_2$  directions. In order to demonstrate the generality of the computer program, an example of non-uniform translation without geometric distortion is discussed. The displacement along a line  $y = \sin x$  for  $0 \le x \le \pi$  is chosen to illustrate non-uniform translation and the results are shown in Figure 16.

Several examples for the case of uniform and non-uniform translations in the presence of geometric distortion (deformation) were solved. The results illustrated that for infinitesimal deformation (linear elasticity), geometric distortion had no effect on the correlation between reference and deformed signal.

Several examples of large deformations on the correlation of reference and deformed signals were considered to determine the accuracy of Equation (40) for large strains. Figures 17 through 19 are examples of the deformed surface P(X') corresponding to large strains without rigid body motion. A comparison of these surfaces with the reference surface, as illustrated in Figure 12, shows the effect of geometric distortion relative to the reference surface. In each example of large geometric distortion the correlation accuracy was the same as the cases considered for uniform translation and infinitesimal deformations.





REFERENCE SCAN AMPLITUDE

Figure 13. Reference signal along the  $X_1$  axis  $P(X_1, 0)$ .



Figure 14. Uniform translation of a point P initially located at the origin.

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Figure 15. Acoustical surface corresponding to a uniform translation without geometric distortion -5 units  $X_1$  direction -8 units in  $X_2$  direction.



Figure 16. Non-uniform translation of a point P initially located at the origin.

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Figure 17. Acoustical surface P(X') corresponding to a large strain  $\varepsilon_{\chi_1} = 0.2$ .









# APPENDIX A

# PROGRAM TO CALCULATE THE AMPLITUDE RATIO FOR A TWO-LAYER ELASTIC HALF SPACE IN A LIQUID

| C<br>C | PROGRAM TO CALCULATE THE AMPLITUDE RATIO<br>FOR A TWO LAYER ELASTIC HALF SPACE IN A |
|--------|---|
| Ċ      | LIQUID<br>FACH NUMBER CORRESPONDS TO AN INTERFACE                                   |
| C      | ENGI ROMER CORRECTORES TO AN INTERINCE  |
| С      | FROPERTIES OF THE LIQUID<br>XLAL=318000.  |
| C      | RHL=+0361<br>PROPERTIES OF SOLID 1  |
| L      | XLA1=16420000.  |
|        | XM1=11600000.   |
|        | RH1=.284  |
| С      | PROFERTIES OF SOLID 2   |
|        | XLA2=/420000.<br>XM2=4000000  |
|        | RH2=+000000.  |
|        | CLL=4863.   |
|        | CL2=20341.  |
|        | CT2=10360.  |
|        | CL1=19348.  |
| r      | LII=10467.<br>LAYER 1IIOUID_SOLID 1 INTEREARE                                       |
| L      | THETA0=20.#3.1416/180.  |
|        | XLAM=XLAL   |
|        | RHD=RHL   |
|        | XLAMB=XLA1  |
|        | XMUB=XM1  |
|        | RHUH=RH1  |
| 7      | WRIIE(3)3)<br>FORMAT(3X.4) TOUTD-SOLID 1 INTEREACE()                                |
| 0      | WRITE(5,4) THETAO   |
| 4      | FORMAT(3X, 'THETA0=', E12.5)  |
|        | CALL WASD(THETAO,XLAM,XMUB,XLAMB,RHO,RHOB)  |
|        |   |
|        |   |
|        |   |
|        | WRITE(5,5) THET31   |
| 5      | FORMAT(3X, 'THETA31=', E12.5)   |
| С      | LAYER 2SOLID 1-SOLID 2 INTERFACE  |
|        | XLAM=XLA1   |
|        | RH0=RH1   |
|        | XLAMB=XLA2  |
|        | XMUB=XM2  |
|        | RHOB=RH2  |
|        | THETAO=THET31   |
| 4      | WRITE(3)6)<br>FORMAT(77, (60) ID 1_60) ID 2 INTERCACE()                             |
| 0      | WRITE(5.7) THETAO   |
| 7      | FORMAT(3X, 'THETA0=', E12.5)  |
|        | CALL SOLID(THETAO,XMU,XLAM,XMUL,XLAME,RHO,RHOB)                                     |
|        | CL=CL1  |
|        | UEBRUEZ ,   |

|      | CALL CRCSUB(CL,THETA0,CLB,YC)<br>THET32=YC  |
|------|---|
|      | WRITE(5.8) THET32   |
| 8    | FORMAT(3X, 'THE)A32=',E12,5)  |
| -    | CALL CRESUB(CL, THETAO, CL, YA)   |
|      |   |
|      | WRITE(5,9) THET12   |
| 9    | FORMAT(3X, 'THETA12=', E12.5)   |
| С    | LAYER 3SOLID 1-LIQUID INTERFACE   |
|      | XLAM=XLA1   |
|      | XMU=XM1   |
|      | RHO=RH1   |
|      | XLAMB=XLAL  |
|      | RHOB=RHL  |
|      |   |
| 4 ^  | WRITE(DIIV)<br>Tooraatiin (oo) II iliidhii Trutte August                            |
|      | FURMARY SAF SULIN IMPLICATE INFERENCE /   |
|      | WRITE(U/II) TREIMU<br>FORMAT(XY,/THETAN-(2F12,5)                                    |
| **   | CALL SOLLI(THETAO,Y)AMAXMUAYEAGARHOARHOB)   |
| r    | LAYER 4SOLTD 2-LIGUDD INTERFACE   |
| 0    | XLAM=XLA2   |
|      | XMU=XM2   |
|      | RHO=RH2   |
|      | XLAMB=XLAL  |
|      | RHOB=RHL  |
|      | THETAO=THE332   |
|      | WRITE(5,12)   |
| 12   | FORMAT(3X, 'SOLID 2-LIQUID INTERFACE')  |
|      | WRITE(5,13) THETAO  |
| 13   | FURMAT(3X) THETADET/EIZ(5)  |
|      | CHEL SULLI(THETHOF/LING/AND/ALHNB/AND/AND/  |
|      | CALL CRCSHB(CL.THETAC.CL.YA)  |
|      | THETA1=YA   |
|      | WRITE(5.14) THET41  |
| 14   | FORMAT(3X, 'THETA41=', E12,5)   |
| ē.   | LAYER 5SOLID 2-SOLID 1 INTENFACE  |
|      | XLAM=XLA2   |
|      | XMU=XM2   |
|      | RHO=RH2   |
|      | XLAMB=XLA1  |
|      | XMUB=XM1  |
|      | RHDH=RH1  |
|      |   |
| a r: | WRITEROFIDE<br>Forwards (south) i thteseast   |
| 10   | PURMENTAL THEREAD   |
| 14   | - WALLENDIE / THEISO<br>- EREMATINY - (THEISO) - (TE12) - 5 (                       |
| 10   | CALL SOLTS/TEFTAO, YELL, 67<br>CALL SOLTS/TEFTAO, YELL, 66, YEUR, Y. AMRIBEO, PHOR) |
|      |   |
|      | CLR=CL1   |
|      | CALL CROSUB(CL, THEYHDICLE, YC)   |
|      | THET35-YC   |

|    | WRITE(5,17) THET35                            |
|----|---|
| 17 | FORMAT(3X, 'THETA35=', E12.5)                 |
| C  | LAYER 6SOLID 1-LIQUID INTERFACE               |
|    | XLAM=XLA1                                     |
|    | XMU=XM1                                       |
|    | RHO=RH1                                       |
|    | XLAMB=XLAL                                    |
|    | RHOB=RHL                                      |
|    | THETAD=THET35                                 |
|    | WRITE(5,18)                                   |
| 18 | FORMAT(3X, 'SOLID 1-L10UID INTERFACE')        |
|    | WRITE(5:19) Inclaid                           |
| 19 | FORMAT(3X, THETAO= , E12,5)                   |
|    | CALL SOLLI (THETAO, XLÓN, FXMU, XLAMB, RHO, R |

CALL SOLLI(THETAO;XLAN;XNU;XLAMB;RHO;RHOB) STOP END

SUBROUTINE WASD(THETAO,XLAM,XMUB,XLAMB,RHO,RHOB) CL=SQRT(XLAM\*2.683/RHO) CLB=SQRT(((XLAMB+2.\*XMUB))\*2.683/RHOB) CTB=SQRT(XMUB\*2.683/RHOB) CALL CRCSUB(CL, THETAO, CL, YA) THETA1=YA WRITE(5,2) THETA1 CALL CRCSUB(CL, THETAO, CLB, YB) THETA3=YB WRITE(5,3) THETA3 CALL CRCSUB(CL, THETAO, CTB, YC) THE TA4=YC WRITE(5,4) THETA4 FORMAT(' THETA1=',F10.4) 2 FORMAT(' THETA3=', F10.4) 4 FORMAT(' THETA4=',F10,4) C11=-SIN(THETA1) C12=SIN(THETA3) C13=-COS(THETA4) C21=COS(THETA1) C22=COS(THETA3) C23=SIN(THETA4) C31=-XLAM/XLAM C32=CL\*(XLAMB+2.\*XMUB\*COS(THETA3)\*COS(THETA3))/(CLB\*XLAM) C33=(CL\*XMUB\*SIN(2.\*THETA4))/(XLAM\*CTB) B1=SIN(THETAO) B2=COS(THETAO) B3=XLAM/XLAM WRITE(5,1) C11,C12,C13,B1 WRITE(5,1) C21,C22,C23,B2 WRITE(5,1) C31,C32,C33,B3 1 FORMAT(1X,E12.5,1X,E12.5,1X,E12.5,1X,E12.5) CALL D3(DETERM,C11,C12,C13,C21,C22,C23,C31,C32,C33) WRITE(5,10) DETERM 10 FORMAT(5X, 'DETERM=', E12.5) CALL D3(DI, B1, C12, C13, B2, C22, C23, B3, C32, C33) X1=DI/DETERM WRITE(5,20) X1 20 FORMAT(5X, 'A1/A0=', E12.5) CALL D3(DII+C11+B1+C13+C21+B2+C23+C31+B3+C33) X2=DII/DETERM WRITE(5,30) X2 30 FORMAT(5X, 'A2/A0=', E12.5) CALL D3(DIII,C11,C12,B1,C21,C22,B2,C31,C32,B3) X3=DIII/DETERM WRITE(5,40) X3 40 FORMAT(5X, 'A3/A0=', E12.5) RETURN END

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SUBROUTINE SOLLI(THETAO,XLAM,XMU,XLAMB,RHU,RHOB) CT=SQRT(XMU\*2.683/RHO) CL=SQRT(((XLAM+2.\*XMU)\*2.683)/RH0) CLB=SQRT(XLAMB\*2.683/RHO) CALL CRCSUB(CL, THETAO, CL, YA) THETA1=YA WRITE(5,2) THETA1 CALL CRCSUB(CL, THETAO, CT, YB) THETA2=YB WRITE(5,3) THETA2 CALL CRCSUB(CL, THETAO, CLB, YC) THETA3=YC WRITE(5,4) THETA3 FORMAT(' THETA1=',F10.4) 2 3 FORMAT(' THETA2=',F10.4) FORMAT(' THETA3=',F10.4) 4 C11=-SIN(THETA1) C12=SIN(THETA2) C13=SIN(THETA3) C21=COS(THETA1) C22=-SIN(THETA2) C23=COS(THETA3) B33=XLAM+2.\*XMU\*COS(THETA0)\*COS(THETA0) C31=(XLAM+2.\*XMU\*COS(THETA1)\*COS(THETA1))/B33 C32=CL\*XMU\*SIN(2.\*THETA2)/(CT\*B33) C33=CL\*XLAMB/(CLB\*B33) B1=SIN(THETAO) B2=COS(THETAO) B3=(XLAM+2.\*XMU\*COS(THETAO)\*COS(THETAO))/B33 WRITE(5,1) C11,C12,C13,B1 WRITE(5,1) C21,C22,C23,B2 WRITE(5,1) C31,C32,C33,B3 WRITE(5,5) B33 FORMAT(1X, E12.5, 1X, E12.5, 1X, E12.5, 1X, E12.5) 1 5 FORMAT(' B33=',E12.5) CALL D3(DETERM,C11,C12,C13,C21,C22,C23,C31,C32,C33) WRITE(5,10) DETERM 10 FORMAT(5X, 'DETERM=', E12.5) CALL D3(DI, B1, C12, C13, B2, C22, C23, B3, C32, C33) X1=DI/DETERM WRITE(5,20) X1 FORMAT(5X, 'A1/A0=', E12.5) 20 CALL D3(DII,C11,B1,C13,C21,B2,C23,C31,B3,C33) X2=DII/DETERM WRITE(5,30) X2 30 FORMAT(5X, 'A2/A0=', E12,5) CALL D3(DIII,C11,C12,B1,C21,C22,B2,C31,C32,B3) X3=DIII/DETERM WRITE(5,40) X3 40 FORMAT(5X, 'A3/A0=', E12.5) RETURN END

SUBROUTINE SOLID(THETAO, XMU, XLAM, XMUB, XLAMB, RHO, RHOB) CL=SQRT((XLAM+2,\*XMU)/RHD) CT=SQRT(XMU/RHD) CLB=SQRT((XLAMB+2,\*XMUB)/RHOB) CTB=SQRT(XMUB/RHOB) CALL CRCSUB(CL, THETAO, CL, YA) THETA1=YA WRITE(5,1) THETA1 CALL CRCSUB(CL, THETAO, CT, YB) THETA2=YB WRITE(5,2) THETA2 CALL CRCSUB(CL, THETAO, CLB, YC) THETA3=YC WRITE(5,3) THETA3 CALL CRCSUB(CL, THETAO, CTB, YD) THETA4=YD WRITE(5,4) THETA4 FORMAT(' THETA1=',E12.5) FORMAT(' THETA2=',E12.5) FORMAT(' THETA3=',E12.5) FORMAT(' THETA4=',E12.5) C11=-SIN(THETA1) C12=-COS(THETA2) C13=SIN(THETA3) C14=-COS(THETA4) C21=COS(THETA1) C22=-SIN(THETA2) C23=COS(THETA3) C24=SIN(THETA4) B33=XMU C31=XMU\*SIN(2.\*THETA1)/B33 C32=(XMU\*CL\*COS(2.\*THETA2))/(CT\*B33) C33=XMUB\*CL\*SIN(2.\*THETA3)/(CLB\*B33) C34=-XMUB\*CL\*COS(2.\*THETA4)/(CTB\*B33) B44=XLAM+2.\*XMU\*CUS(THETA0)\*COS(THETA0) C41=-(XLAM+2.\*XMU\*COS(THETA1)\*COS(THETA1))/B44 C42=XMU\*CL\*SIN(2.\*THETA2)/(CT\*B44) C43=CL\*(XLAMB+2.\*XMUB\*COS(THETA3)\*COS(THETA3))/(CLB\*B44) C44=XMUB\*CL\*SIN(2.\*THETA4)/(CTB\*B44) B1=SIN(THETAO) B2=COS(THETAO) B3=XMU\*SIN(2.\*THETA0)/B33 B4=(XLAM+2.\*XMU\*COS(THETAO)\*COS(THETAO))/B44 WRITE(5,5) C11,C12,C13,C14,B1 WRITE(5,5) C21,C22,C23,C24,B2 WRITE(5,5) C31,C32,C33,C34,B3 WRITE(5,5) C41,C42,C43,C44,B4 FORMAT(1X,E12.5,1X,E12.5,1X,E12.5,1X,E12.5,1X,E12.5) CALL D4(DETERM;C11;C12;C13;C14;C21;C22;C23;C24;C31; XC32,C33,C34,C41,C42,C43,C44) WRITE(5,10) DETERM FORMAT(5X, 'DETERM=', E12.5)

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|    | CALL D4(DI,B1,C12,C13,C14,B2,C22,C23,C24,      |
|----|--|
|    | XB3+C32+C33+C34+B4+C42+C43+C44)                |
|    | X1=DI/DETERM                                   |
|    | WRITE(5,20) X1                                 |
| 20 | FORMAT(5X,'A1/A0=',E12.5)                      |
|    | CALL D4(DII,C11,B1,C13,C14,C21,B2,C23,C24,C31, |
|    | XB3,C33,C34,C41,B4,C43,C44)                    |
|    | X2≈DII/DETERM                                  |
|    | WRITE(5,30) X2                                 |
| 30 | FORMAT(5X, 'A2/A0=', E12.5)                    |
|    | CALL D4(DIII,C11,C12,B1,C14,C21,C22,B2,C24,    |
|    | XC31,C32,B3,C34,C41,C42,B4,C44)                |
|    | X3≈DIII/DETERM                                 |
|    | WRITE(5,40) X3 ·                               |
| 40 | FORMAT(5X,'A3/A0=',E12.5)                      |
|    | CALL D4(DIV,C11,C12,C13,B1,C21,C22,C23,B2,C31, |
|    | XC32,C33,B3,C41,C42,C43,B4)                    |
|    | X4≈DIV/DETERM                                  |
|    | WRITE(5,50) X4                                 |
| 50 | FORMAT(5X,'A4/A0=',E12.5)                      |
|    | RETURN   |
|    | END  |

```
SUBROUTINE D4(D,A11,A12,A13,A14,A21,A22,A23,A24,A31,A32,
XA33,A34,A41,A42,A43,A44)
 CALL D3(DA, A22, A23, A24, A32, A33, A34, A42, A43, A44)
 CALL D3(DB,A21,A23,A24,A31,A33,A34,A41,A43,A44)
 CALL D3(DC,A21,A22,A24,A31,A32,A34,A41,A42,A44)
 CALL D3(DD,A21,A22,A23,A31,A32,A33,A41,A42,A43)
 D=A11*DA-A12*DB+A13*DC-A14*DD
 RETURN
 END
 SUBROUTINE D3(D,A11,A12,A13,A21,A22,A23,A31,
XA32+A33)
 CALL D2(DE,A22,A23,A32,A33)
 CALL D2(DF,A21,A23,A31,A33)
 CALL D2(DG,A21,A22,A31,A32)
 D=A11*DE-A12*DF+A13*DG
 RETURN
 END
 SUBROUTINE D2(D,A11,A12,A21,A22)
 D=A11*A22-A12*A21
 RETURN
 END
 SUBROUTINE CRCSUB(A,B,C,Y)
X=A*SIN(B)/C
Y=X+(X**3.)/6.+3.*(X**5.)/40.+5.*(X**7.)/112.
X+35.*(X**9.)/576.
```

RETURN END

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APPENDIX B

TWO-DIMENSIONAL CORRELATION OF TWO LINES X = Y = UNIFORM TRANSLATION

|              | - DIMENSIUN A(100,1000, AX(10),AY(10),D1(1,100) |
|--------------|---|
|              | READ(7,10) N, M, NF                             |
|              | READ(7+11) DELX                                 |
| : 0          | FORMATCULAY                                     |
| 11           | FORMAT(FIU.4)                                   |
|              | DO LO ISLANAL                                   |
|              | DO 13 J-1+N+1                                   |
| ي.<br>است در | 存(19月)の(3.6)                                    |
| 12           | CONTINUE  |
|              | READ(7,20) (DI(1,1),1 1,100)                    |
| C C          | FORMAT(F10.4)                                   |
|              | DO 3 1-1,100,1                                  |
|              | A(I+1)=D1(1+1)                                  |
|              | A(1,1)=DT(1,1)                                  |
| 3            | CONTINUE  |
|              | DO 5 I=1,99,1                                   |
|              | DO & J=1,99,1                                   |
| Ċ            | A(1+1,J(1)=A(I+1,1)*A(1,J+1)/3.                 |
| 5            | CONTINUE  |
|              | K=NM  |
|              | DO 9 HM=0+K+M                                   |
|              | NN=MM   |
|              | 107 I = 1.001                                   |
|              | AX(I)=A(MM+1/I+NN)                              |
|              | AY(I) = A(I + MM + NN + 1)                      |
| 7            | CONTINUE  |
|              | CALL CORRI(A,AX,AY,N,M,NP)                      |
| 9            | CONTINUE  |
|              | STOP  |
|              | END   |
|              |   |

| L  |  |
|----|--|
|    | SUBROUTERE CORRECAPAX, AT, N, M, IC)   |
|    | WR11E(5+30)  |
| 30 | FURMAT(UX, (CORKI))  |
|    | DIMENSION AC100/100//AX(10)/AY(10)   |
|    | S2=10E20   |
|    | し2=10日20   |
|    | INM=0  |
|    | LMM=0  |
|    | ICNM=N-M   |
|    | 10 2 J=1,ICNN,1  |
|    | DO 1 L=0,ICNM,1  |
|    | S=0,0  |
|    | C=0.0  |
|    | DO 3 II=1,M/1  |
|    | SI=AX(II)-A(J,II+L)  |
|    | CIHAY(II)-A(II+L+J)  |
|    | S=S+S1*S1  |
|    | C=C+C1*C1  |
| 3  | CONTINUE   |
|    | IF(S.LT.S2) INM=L  |
|    | IF(S.LT.S2) S2=S   |
|    | IF(C.LT.C2) IMN=L  |
|    | IF(C+LT+C2) C2≕C   |
| 1  | CONTINUE   |
| 2  | CONTINUE   |
|    | DX=0.001*FLDAT(INM*IC)   |
|    | DY=0.001*FLOAT(1MN*IC)   |
| -  | WRITE(5,9) S2  |
| 9  | FURMAT(5X) LUKKELATIUN-X= JEI2+0/  |
| -  | WRITE(S#7) 62<br>Commany Common Trol Mark C10 EN                                       |
| /  | FURMAI(5X; LURREALIIUN-T= )E12.5/  |
| ~  | WRITE(D)8) DX/DT<br>moonartery (nyme) E40 7 7V-(nyme)-E10 7                            |
| d  | HOROBELOXA, DXB, ALTOPONOVA, DIM, ALTOPON<br>HOROBELOXA, DXB, ALTOPONOVA, DIM, ALTOPON |
|    |  |
|    |  |

CORRI CORVELATION-X= 0.000000000 CORREALTION-Y= 0.000002+00 0.000 DY= 0.000 TIX == CORR1 CURRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 ItX≈ 0.005 10.4 0.005 CORRI CORRELATION-X- 0.00000E+00 CORREAL T CON-Y= 0.00000E+00  $\mathbf{D}\mathbf{X} =$ 0.010 117-0.010 CORRI CORRELATION-X= 0.00000E+00 CURREAL / 10N-Y= 0.00000E+00 0.015 DY= ÐX≈ 0.015 CURRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 [iX= 0.020 DY= 0.020 CORRI CORRELATION-X= 0.00000E+00 CURREALTION-Y= 0.00000E+00 1)X= 0.025 DY= 0.025 CORRI CORRELATION-X= 0.00000E+00 CORREAL / 10N-Y= 0.00000E+00 DX= 0.030 BY= 0.030 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 LIX= 0.035 DY= 0.035 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 £XX≈ 0.040 UY= 0.040 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 DX= 0.045 DY= 0.045 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 ΩX= 0.050 Div 0.050

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CORRI CORRELATION-X= 0.000000+400 CORREALTION-Y= 0.00000E+00 DΧ≕ 0.055 10Y == 0.055 CORRT CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 0+040 DYm 0.060 DX≕ CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0,00000E+00 DX= 0.065 DY≕ 0.065 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00  $\Pi X =$ 0.070 DY= 0.070 CORRI CORRELA) ION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 0.075 DY= ₽X≖ 0.075 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 0.080 1ιY= 0.080 DX= CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 0.085 DY= 0.085 DX≔ CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 DX= 0.090 DY= 0.090 CORRI CORRELATION-X= 0.00000E+00 CORREALTION-Y= 0.00000E+00 0.095 DY= ŪX≈ 0.095 -----

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