STUDY OF AIR-SOLID INTERFACE WAVE BY LASER ULTRASONICS

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Abstract

The displacement of Scholte wave at the air-solid interface generated by a disk-like laser pulse source is calculated with contours integration and Cagniard de-Hoop method. The Scholte waves at the air-metal interface are detected and its velocity is measured by laser ultrasonic technique. It shows that the pulse width of Scholte wave is mainly dependent on the acoustic time delay on the diameter of thermoelastic source and its velocity is close to the sound velocity in the air.

Introduction

The Scholte wave is an interface wave at fluid-solid boundary. The Scholte wave at liquid-solid interface[(1-3)] is widely studied since 1939. In 1949 Scholte pointed out that there were two waves at liquid-solid interface, one is Leaky Rayleigh wave near solid surface, another is near liquid boundary and its velocity is little smaller than that in liquid.

The interface wave at gas-solid boundary had been predicted theoretically by Brekhovskikh and discussed in its velocity[(4)]. Godinez-Azcuaga and L.Adler showed that there were three surface waves propagating on the interface between air and fluid-saturated porous material[(5)]. They are called Rayleigh, slow Rayleigh and airborne wave, in which the airborne wave is the Scholte wave at air-solid interface, but they did not verified it in their experiments with PZT transducer.

Laser ultrasonic method is a non-contact and very effective detecting technique for study of the Scholte wave at air-solid interface[(6,7)] expeimentally. The Scholte wave at fluid-solid interface generated with a line pulse laser source has been discussed by Gusev et al[(7)]. In this paper the Scholte wave at air-solid interface generated with a disk-like laser pulse source is discussed theoretically and some experimental results are introduced.

1. Calculation of Scholte wave displacement at air-solid interface

When a pulse laser impacts onto the air-metal interface, a temperature increment is produced near metal interface by the absorbed light energy. Because the optical penetration depth in metal and the thermal diffusion lengths in air and metal are very smaller than acoustic wavelength and diameter of laser beam, the temperature increment generated by laser pulse can be simply considered as a surface source:

$$T(r,z,t) = R(r)\delta(t)\delta(z) \qquad (1)$$

where $$R(r)=\begin{cases} \pi/2 & r<a \\ \sin^{-1}(a/r) & r<a \end{cases} \qquad (1a)$$

in which a is the equivalent radius of the pulse laser beam (Fig.1).

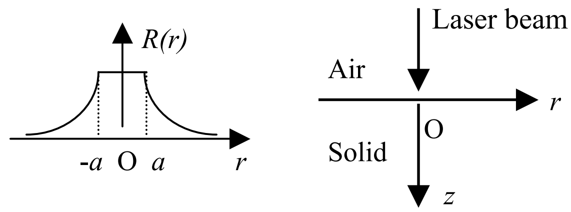

Fig.1 Laser-sample system

The double Laplace and zero-order Hankel transforms of Eq.(1a) is

$$\overline{T^{*}}(p,s) = (ap)^{-2}\sin(ap) \qquad (1b).$$

where s and p are Laplace and Hankel transform variables, respectively.

Using the field potential notion ϕ and $\mathbf{H}(0,-\psi_r,0)$, the thermo-elastic stress and displacement in the axial symmetry case for a homogeneous and isotropic medium can be expressed:

$$\sigma_{zz}(r,z,t)=\rho\left(1-2\frac{c_T^2}{c_L^2}\right)\ddot{\phi}+2\rho c_T^2\left(\psi'_{,zz}-\frac{\ddot{\psi}'_{,z}}{c_L^2}+\psi'_{,zzz}\right)-2\rho GT\frac{c_T^2}{c_L^2} \qquad (2)$$

$$\sigma_{rz}(r,z,t)=\mu\left(2\phi_{,z}+2\psi'_{,zz}-\frac{\ddot{\psi}}{c_T^2}\right)_{,r} \tag{3}$$

$$u_z(r,z,t)=\phi_{,z}+\psi'_{,zz}-\frac{\ddot{\psi}}{c_T^2} \tag{4}$$

where c_L, c_T are the longitudinal and the transversal wave velocity respectively and $G=\alpha_T B_T/\rho$, B_T and α_T are the volume and thermal expansion coefficient of the medium, respectively.

The wave motion of ϕ and ψ satisfy:

$$c_L^2\nabla^2\phi(r,z,t)=\ddot{\phi}(r,z,t) \tag{5}$$

$$c_T^2\nabla^2\psi(r,z,t)=\ddot{\psi}(r,z,t) \tag{6}$$

Applying Laplace-Hankel transformations to Eqs.(2) to (6), the transformed solutions in solid and air have the forms

$$\bar{\phi}^*(p,z,s)=Ae^{-k_{Lz}z},\ \bar{\psi}^*(p,z,s)=Be^{-k_{Tz}z},\ (z>0) \tag{7}$$

$$\bar{\phi}_f^*(p,z,s)=A_f e^{k_{fz}z},\ \bar{\psi}_f^*(p,z,s)=0,\qquad (z<0) \tag{8}$$

where $k_{Lz}^2=p^2+k_L^2$, $k_{Tz}^2=p^2+k_T^2$, $k_{fz}^2=p^2+k_f^2$ and

$$k_L^2=\frac{s^2}{c_L^2},\ k_T^2=\frac{s^2}{c_T^2},\ k_f^2=\frac{s^2}{c_f^2}$$

and the coefficients A, B and A_f are determined by applying the boundary conditions

$$\bar{\sigma}_{zz}^*(p,0,s)=\bar{\sigma}_{zzf}^*(p,0,s)\ ,\quad \bar{\sigma}_{rz}^*(p,0,s)=0$$

$$\bar{u}_z^*(p,0,s)=\bar{u}_{zf}^*(p,0,s)$$

Then the transformed solution of $\bar{u}_{zf}^*(p,0,s)$ is found to be

$$\bar{u}_{zf}^*(p,0,s)=-\frac{2Gk_{Lz}k_T^2\bar{T}^*}{c_L^2\Delta_{sch}} \tag{9}$$

where

$$\Delta_{Sch}=(k_T^2+2p^2)^2-4p^2k_{Lz}k_{Tz}+\frac{\rho_f k_{Lz}}{\rho k_{fz}}k_T^4 \tag{10}$$

is the "Scholte-wave denominator".

Substituting $\overline{T^*}$ of Eq.(1b) into Eq.(9) and making inverse Hankel transformation first, we get

$$\bar{u}_{zf}(r,0,s)=-\frac{2G}{ac_T^2}\int_0^\infty\frac{k_{Lz}k_T^2}{\Delta_{sch}}\frac{\sin(ap)}{ap}J_0(pr)dp \tag{11}$$

Using formula

$$J_0(pr)=\frac{1}{\pi i}\int_0^\infty(e^{iprch\theta}-e^{-iprch\theta})d\theta$$

and let $p=k_Tx=sx/c_T$, $\beta^2=\frac{c_T^2}{c_L^2}$, $\gamma^2=\frac{c_T^2}{c_f^2}$, Eq.(11) becomes

$$\bar{u}_{zf}(r,0,s)=\frac{i2G}{\pi ac_L^2}[M_1(r,s)-M_2(r,s)] \tag{12}$$

where

$$M_{1,2}(r,s)=\int_0^\infty d\theta\int_0^\infty m(x)\sin c\left(\frac{sa}{c_T}x\right)e^{\pm i\frac{sr}{c_T}xch\theta}dx \tag{13}$$

and

$$m(x)=\frac{(x^2+\beta^2)^{1/2}}{(1+2x^2)^2-4x^2(x^2+\beta^2)^{1/2}(x^2+1)^{1/2}+\frac{\rho(x^2+\beta^2)^{1/2}}{\rho_f(x^2+\gamma^2)^{1/2}}}=\frac{N(x)}{D(x)} \tag{14}$$

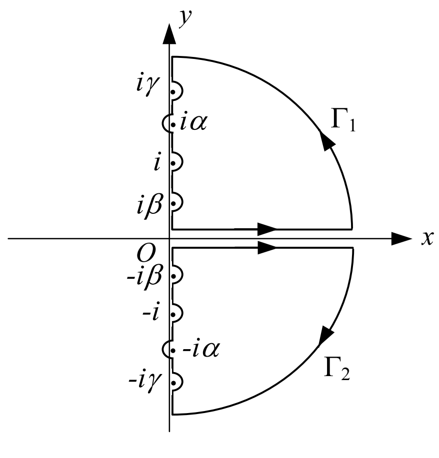

Fig.2 Contours of integration for $M_{1,2}(r,s)$

To do the integration in $M_{1,2}(r,s)$ with respect to x, we extend the integral variable x into the complex plane $w=x+iy$ and use the integral contours $\Gamma_{1,2}$ as shown in Fig.2. The integrand of w has three pairs of branch points at $w=\pm i\beta$, $w=\pm i$, $w=\pm i\gamma$. To obtain the Scholte wave contribution, one pairs of poles at $w_{sch}=\pm i\alpha$ with $\alpha=\frac{c_T}{c_{sch}}$ corresponding to the Scholte wave roots of $\Delta_{sch}=0$ are taken into consideration. We can write

$$M_{1,2}(r,s)=\int_0^\infty d\theta\Big[\int_0^\infty \pm im(\pm iy)\sin(\pm i\frac{sa}{c_T}y)e^{\frac{\mp sr}{c_T}ych\theta}dy+i2\pi\mathrm{Res}(\pm i\alpha)\Big] \tag{15}$$

where Res $(\pm i\alpha)$ are the residues at $w_{sch}=\pm i\alpha$ and is calculated by

$$\mathrm{Res}\,(+i\alpha)=\frac{N(w)\sin(k_T w)}{D'(w)k_T}e^{ik_T wrch\theta}\Big|_{w=i\alpha}=-\mathrm{Res}\,(-i\alpha)$$

Therefore the Laplace transformed displacement of the Scholte wave is found from Eq. (12)

$$\overline{u^*_{fz}}(r,0,s)=-4\frac{Gc_T N(i\alpha)}{a^2c_L^2D'(i\alpha)}\int_0^\infty\frac{1}{s}\sin(i\frac{sa}{c_{sch}})e^{-\frac{sr}{c_{sch}}ch\vartheta}d\theta \tag{16}$$

Based on the properties of the Laplace transformation, the particle velocity of Scholte wave is

$$\overline{v^*_{fz}}(r,0,s)=2i\frac{Gc_T c2N(i\alpha)}{a^2c_L^2D'(i\alpha)}\int_0^\infty\Big[e^{-\frac{s(rch\theta+a)}{c_{sch}}}-e^{-\frac{s(rch\theta-a)}{c_{sch}}}\Big]d\theta \tag{17}$$

Let $t=\frac{rch\theta\pm a}{c_{sch}}$ and $dt=\sqrt{(t\pm\frac{a}{c_{sch}})^2-(\frac{r}{c_{sch}})^2}\,d\theta$, the particle velocity in time domain can be obtained using Cagniard de-Hoop method:

$$v_{fz}(r,0,t)=2i\frac{Gc_T N(i\alpha)}{a^2c_L^2D'(i\alpha)}\Bigg\{\frac{H(t+\frac{a}{c_{sch}}-\frac{r}{c_{sch}})}{\sqrt{(t+\frac{a}{c_{sch}})^2-(\frac{r}{c_{sch}})^2}}-\frac{H(t-\frac{a}{c_{sch}}-\frac{r}{c_{sch}})}{\sqrt{(t-\frac{a}{c_{sch}})^2-(\frac{r}{c_{sch}})^2}}\Bigg\} \tag{18}$$

Finally, we get the time domain displacement of Scholte wave by integrating Eq.(15):

$$u_{fz}(r,0,t)=2i\frac{Gc_T N(i\alpha)}{c_L^2D'(i\alpha)}\int\Bigg\{\frac{H(t-\frac{r}{c_{sch}}-\frac{a}{c_{sch}})}{\sqrt{(t-\frac{a}{c_{sch}})^2-(\frac{r}{c_{sch}})^2}}-\frac{H(t-\frac{r}{c_{sch}}+\frac{a}{c_{sch}})}{\sqrt{(t+\frac{a}{c_{sch}})^2-(\frac{r}{c_{sch}})^2}}\Bigg\}dt \tag{19}$$

To give an example, the calculated results of displacement u_{fz} at air-Fe interface are shown in Fig.3 where different laser impact radius a are used. It is shown that the Scholte wave pulse width depends on the acoustic time delay $2a/c_{sch}$.

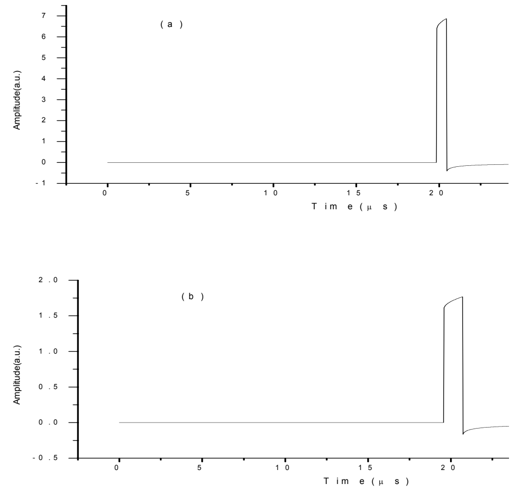

Fig.3 Calculated results of u_{fz} (r,0,t) for an observation distance from the source point r=7mm with laser impact radius (a) a=0.1mm, (b) a=0.2mm.

2. Experimental results

The Scholte waves at air-steel interface detected by laser ultrasonic system is shown in Fig.4. The flight time t_R of Rayleigh wave and t_{sch} of Scholte wave are 2.50 μS and 20.60 μS, respectively. For comparison, in the theoretical calculation, the Rayleigh singularity

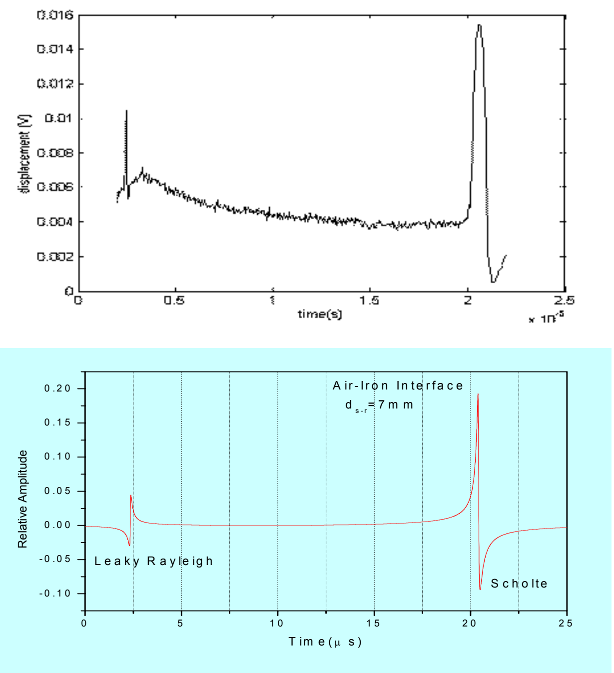

Fig.4 The experimental (top) and calculated (bottom) results of interface waves at air-steel interface. The distance between the source and the receiver r = 7mm, laser power E=4mJ, λ = 0.533μm, the signal is averaged 1024 shots.

contribution is also taken into consideration and the temporal distribution of the laser pulse line source is taken as $(t/t_0)\exp(-t/t_0)$. It is in good agreement between the experimental and the theoretical results.

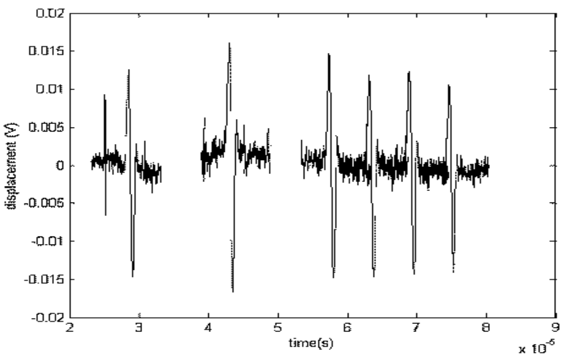

Fig.5 The interface waves on the air-Al interface at r=10, 15, 20, 22, 24, and 26mm between a line laser pulse source and receiver. The sound speed is 0.3475mm/µS at 26.5 ^{o}C.

The Scholte waves at air-Aluminum interface at different r^i between the source and the receiver has been measured and shown in Fig.5. The Scholte wave velocity at 26.5 ^{o}C has been determined by a linear interpolation method:

$$r^i = r_0 + t^i c_{sch}$$

and we get c_{sch} = 0.3475 mm/µS. It is proved that the Scholte wave velocity is close to the sound velocity in the air.

3. Conclusions

The displacement of Scholte wave at air-solid interface generated by a disk like pulse laser source is calculated with contours integration and Cagniard de Hoop methods. The Scholte wave at air-metal interface is generated and detected by laser ultrasonic technique. It is shown that its velocity is very close to the sound velocity in the air. Its pulse width is dependent on its acoustic delay time $2a/c_{sch}$ at the diameter of generating source mainly. The experimental and theoretical results are in good agreement.

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References

1. A. de Hoop, Van der Hijder, “Generation of acoustic waves by an impulsive point source in a fluid/solid configuration with a plane boundary”, J. Acoust. Soc. Am., **75** (6), 1709, (1984).
2. B.Poiree, F.Luppe, “Evanescent plane waves and the Scholte-Stoneley interface wave”, J. Acoustique, 4, 575, (1991).
3. F. Luppe, J. Doucet, “Experimental study of the Stoneley wave at a plane liquid-solid interface”, J. Acoust. Soc. Am., **83** (4), 1276-1279, (1988).
4. L.M.Brekhovskikh, “Waves in layered media”, Academic, NewYork, 1980 2nd ed.
5. V Godinez-Azcuaga, L Adler, “Theoretical simulation of experimental observations of surface wave propagation on a fluid-saturated porous material”, Rev. of Progress in QNDE”, 14, 243, (1995).
6. K. V. de Rostyne, C. Glorieux, Gao Wei-min, W. Lauriks and J. Thoen, “laser ultrasonic measurements of acoustic waves generated at solid-liquid interfaces”, ACTA Physica Sinica, Vol.8 suppl., s219 (1999).
7. V. Gusev, C. Desmet, W. Lauriks, “Theory of Scholte, Leaky Rayleigh and Lateral wave excitation via the laser-induced thermoelastic effect”, J. Acoust. Soc. Am., **100** (3) 1514, (1996).