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Influence of acoustic leakage at fluid–solid interface on interferometric detection of surface acoustic wave

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ABSTRACT

When using laser interferometer to detect surface acoustic wave at fluid–solid interface, there are two factors which will cause the optical path length variation of the probe laser beam: interface deformation, and refractive index changes in fluid induced by acoustic leakage. Influence of acoustic leakage on laser interferometric detection for surface acoustic wave is researched here. A metal plate immersed in an infinite fluid is used as a physical model. Interface deformation due to laser-induced acoustic wave and pressure in fluid due to acoustic leakage are computed for select cases by finite element method. The optical path length variation caused by the two factors are calculated respectively and compared. The results show that the influence of acoustic leakage increases with the increasing acoustic impedance matching of fluid and solid, the peak-to-peak of influence degree increases linearly with the increasing acoustic impedance of fluid, and that decreasing the distance between the interferometer and interface can effectively reduce the influence of acoustic leakage.

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1. Introduction

There have been extensive studies on surface acoustic wave at fluid–solid interface due to its potential application in seismology, engineering, and non destructive test (NDT) [1–3]. However, its detection is still an urgent problem although there are many methods for measurement of surface acoustic wave. In fact, the most popular method for detection of surface acoustic waves is the transducer one, where the surface acoustic wave signal is detected by a piezoelectric transducer attached to the surface of the solid [4]. Unfortunately, it was pointed out that the acoustic connection between the sample and the transducer will influence the ultrasonic field. In this respects, noncontact measurements are desirable. One method is to employ interferometric detection which can detect without contact ultrasonic field and has a wide responsive bandwidth, so that it was extensively used to detect surface acoustic wave [5–11]. In this technique, the normal surface displacement is deduced from the optical path length variation of a laser beam reflected by the surface.

Actually, it was pointed out recently that when surface acoustic wave propagates along fluid–solid interface, the energy of the wave "leaks" into the fluid [12], that will cause the refractive index changes in fluid as a function of both time and space, altering the optical path length of laser beam which propagates in the fluid. As a result, expecting the surface displacement, there is the other factor which induced the optical path length variation of the laser probe beam in interferometric detection, that is refractive index change in fluid induced by acoustic leakage. In previous studies, the acoustic leakage factor is always ignored and the important subject, namely the influence of acoustic leakage on interferometric detection, did not arouse the researchers' attention until now, which will directly influence the correctness of the results presented by laser interferometric sensor. In this paper, the influence of acoustic leakage in fluid on interferometric detection was researched. Laser-induced interface acoustic field is computed by finite element method due to its advantages and universal application of laser ultrasonic. Two optical path length variation of laser probe beam caused by these two factors are calculated respectively and compared.

2. Interferometric detection of surface acoustic wave

Numerous optical interferometries have been developed for detecting surface acoustic wave, such as Michelson interferometry, Mach–Zender interferometry, heterodyne interferometry [7–10]. These devices use the mechanism that the displacement of a vibrating surface is obtained by measuring the optical path length variation of the probe beam due to the motion of the reflected surface.

The schematic diagram of laser ultrasonic system is shown in Fig. 1. The optical probe beam from laser interferometer crosses a transparent fluid where the index of refraction is modulated by the

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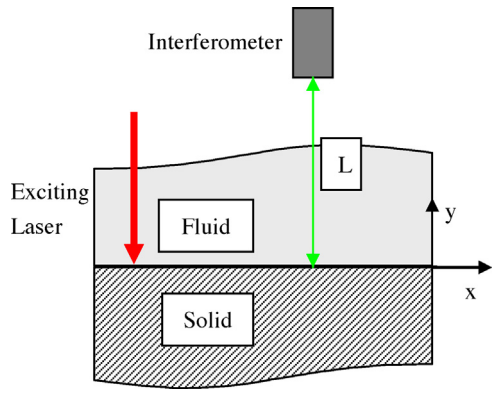

Fig. 1. Schematic of laser ultrasonic system.

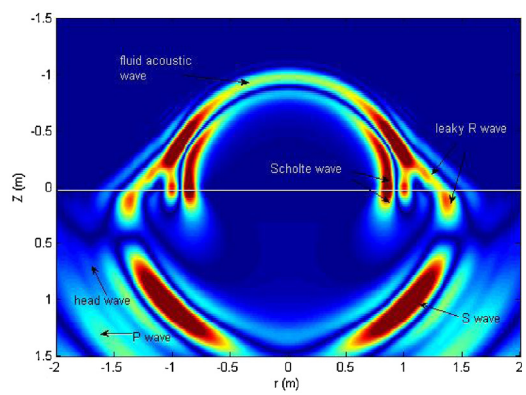

Fig. 2. Absolute value of pressure (in water) and stress (in solid) field snapshot at $t = 0.72$ ms given by finite element analysis. The interface is subject to a transient point load that varies with time as $f(t) = \sin^2(\pi t/T)$ with $T = 200$ μs.

acoustic wave and is then reflected by a solid surface. The phase-modulated current measured by the laser interferometer is given as

$$i(t) \sim \cos\left[\delta(t) + \phi_s - \phi_R\right] \tag{1}$$

where ϕ_R and ϕ_s are the phase constants corresponding to the reference and the probe beams of the interferometer. $\delta(t)$ is the optical path length variation of probe laser due to the ultrasonic waves and includes two phase changes respectively induced by normal surface displacement (δ_s) and acoustic leakage modulated refraction index (δ_R) for fluid–solid interface case.

$$\delta_S = -2U_y n_0 \tag{2}$$

$$\delta_R = 2\int_0^L \Delta n dy \tag{3}$$

where U_y is the normal displacement of the solid surface, n_0 is the refractive index of the fluid when there is no acoustic wave present, L is the distance between the interferometer and the interface.

Consider a traveling wave in fluid due to acoustic leakage, the variation in the index of refraction index (Δn) is proportional to the acoustic variation in pressure (Δp). For a liquid such as water,

$$\Delta n = \frac{1}{2}\sqrt{\frac{M}{\rho c}}\Delta p \tag{4}$$

For a gas such as air,

$$\Delta n = \frac{(n_0 - 1)\Delta p}{\rho c^2} \tag{5}$$

Table 1
Parameter of steel solid.

Density	Longitudinal velocity c_L (m/s)	Shear velocity c_s (m/s)	Acoustic impedance
7800	5980	3246	4.6644×10^7

Table 2
Fluid media.

Designation	Density, ρ_f (kg/m^3)	Dilatational velocity, c_f (m/s)	Acoustic impedance
Water	1000	1500	1.5×10^6
Air	1.21	343	415.03
F1	1000	1250	1.25×10^6
F2	1000	1000	1×10^6
F3	1000	961	9.61×10^5
F4	1000	343	3.43×10^5
F5	76.5	1500	1.1475×10^5
F6	1.21	1500	1.815×10^3
F7	76.5	343	2.62395×10^4

where M is the material parameter, ρ is density, and c is the speed of sound in the fluid.

To determine the influence of acoustic leakage on interferometric detection, it is necessary to firstly determine the acoustic variation in pressure in fluid caused by acoustic leakage and the normal displacement on solid surface. However, it is very difficult for experiment measurement, so numerical calculation is applied for acoustic field in fluid and solid. In this paper, finite element method was introduced to numerically simulate laser-induced ultrasonic wave on fluid–solid interface.

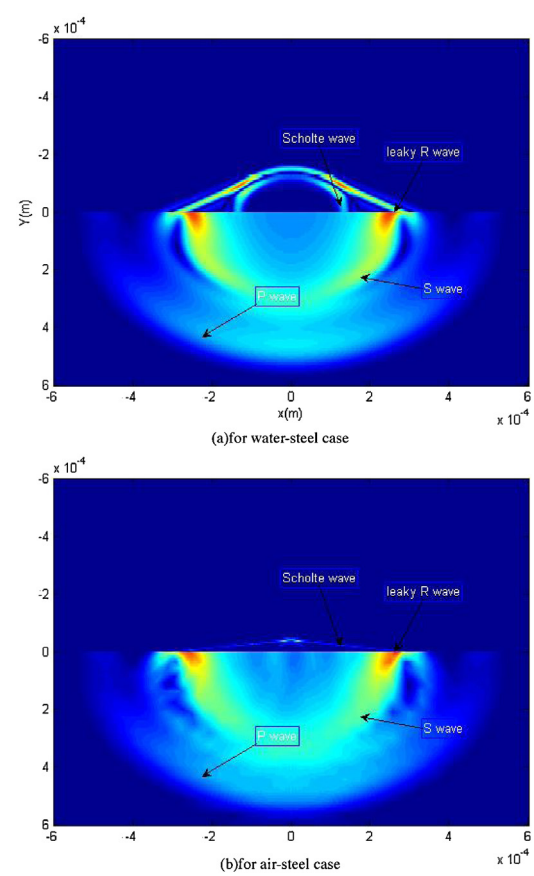

Fig. 3. Absolute value of pressure (in fluid) and displacement (in steel solid) field snapshot at $t = 0.11$ μs given by finite element analysis.

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