An optical heterodyne acoustic imaging employing a plastic film detector

PACS number: 43. 35. Sx

S. Nagai & K. Iizuka
National Research Laboratory of Metrology, 1-1-4, Umezono, Sakura-Mura, Ibaraki, 305 Japan (Received 22 September 1980)

This paper describes a system for ultrasonic imaging which features high resolution, high stability to the ambient disturbance and no restrictions on the acoustic pulse form. The wavelength-limited resolution is realized and the acoustic wave displacement as small as 1 Å is measured with optical heterodyne detection. As the acoustic wave strikes the solid/water interface, it generates the dynamic deformation on the solid surface. The surface motion at an ultrasonic frequency \( f_s \) is detected with heterodyning the reflected light from the surface and the reference light, which is shifted in frequency by an amount of \( f_m \) from original optical frequency. This process produces three different beat frequencies \( f_m \pm f_s \), \( f_m \). The beat currents \( i_A \) at \( f_m \) and \( i_B \) at \( f_m \pm f_s \), are proportional to \( J_0(\delta) \) and \( J_1(\delta) \), respectively, where \( \delta = 2\pi f_m/\lambda \), \( \lambda \) is the surface displacement, \( \lambda \) the optical wavelength, \( J_0 \) and \( J_1 \) are Bessel functions of the first kind. Since the displacement is small as compared with \( \lambda \), the image information is retained only in \( i_B \).

Application of this method to acoustic imaging was first proposed by Massey,\(^1\) followed by Green et al.\(^3\). In their experimental works acousto-optic conversion was made with the metallized glass plate immersed in water. As the substantial impedance mismatch between water and glass causes multi-reflection in glass, the motion of the glass surface does not faithfully reproduce the incident acoustic distribution.

Recently Mezrich et al.\(^5\) proposed the plastic film as an area acoustic detector. The film is thin and its acoustic impedance is close to that in water. The film moves almost exactly as the acoustic wave in water. This motion was measured by a modified Michelson interferometer. The ambient disturbance, such as air current, thermal drift, was suppressed with a wiggler (vibrating mirror). However there are some constraints on the shape of the acoustic pulse. The square envelope is desirable. When this condition is not fulfilled, the signal current would depend on the peak-detected part of the acoustic pulse and for short pulses below 10 \( \mu s \) this method does not work well, though they have settled these shortcomings in a sophisticated way.\(^5\) While the optical heterodyne method is free from above restrictions and immune to ambient disturbance.

The experimental setup is shown in Fig. 1. The system operates at 1.5 MHz (\( f_s \)) with a pulse length of about 20 \( \mu s \). The acoustic wave from a ceramic transducer impinges on the test piece. The scattered wave produces an acoustic image through a concave acoustic lens on the polyester film detector coated with Al (10 \( \mu m \) thick and 100 mm in diameter), which is a key component of this system. The photo of a film holder is presented in Fig. 2. The holder is composed of two brass concentric cylinders fitted each other. The film is attached on one end of the outer cylinder and pulled around the edge of the inner one. The tension is adjusted by screwing the inner one back and forth.

The light beam from He–Ne laser is modulated by the Bragg cell, in which the acousto-optic interaction is made through glass. The unshifted zeroth order diffracted light is deflected by galvanometers \( G_1 \) horizontally and \( G_2 \) vertically, and strikes the film. The beam spot is about 0.5 mm in diameter and scans in a raster pattern on the film surface. The system covers 80\(^\times\)80 resolution elements and has a frame time of about 6.4 s, considering that the scan speed is 1000 elements/s. The galvanometer \( G_1 \) is situated at the focal plane of lens \( F_1 \). This configuration keeps the light incident normally onto the film. The first order diffracted light, whose frequency shift \( f_m \) is 30 MHz, serves as the optical local oscillator. The reflected light is phase-modulated with a modulation index \( \delta \). The reflected and reference light enter collinearly onto a photomultiplier through a 0.5 mm diameter pinhole and produce the sideband current \( i_B \) at 28.5 or 31.5 MHz. This signal is filtered by a tuned amplifier with 80 kHz bandwidth and fed to a receiving gate. The gate is opened by the trigger signal synchronized to the acoustic pulse wave. The signal is sampled and integrated during the gate width, which is equal to the acoustic pulse width. The acoustic image is displayed on a storage CRT.

The optical heterodyne technique is sensitive to the angular mismatch of the signal and reference light. The angular variation of the signal light, when scanned the whole image area, was \( \pm 0.5^\circ \), which includes the error due to departure from flatness in the film and misalignment of the optical system etc. This angular variation led to \( \pm 10\% \) signal current change.

Examples of acoustic images are presented in Fig. 3. The lateral resolution \( d \) was about 2 mm, which agreed with the theoretical value of 2.6 mm derived from the equation \( d = \lambda / (2 \times \text{N.A.}) \) (N.A.: numerical aperture =...
Fig. 1 Block diagram of experimental setup.


The sensitivity was determined from the fact that the currents $i_A$ and $i_B$ are related to the value $J₁(δ)/J₀(δ)$ by $i_B/i_A = J₁(δ)/J₀(δ)$. The threshold displacement is derived by equating $i_B$ to the noise current at 28.5 MHz. Experimentally $i_A$ was 60 dB higher than the noise current at 28.5 MHz. Thus the threshold displacement is given by $J₁(δ)/J₀(δ) \approx \frac{2\pi Z}{\lambda} = 10^{-4}$. This equation yields $Z = 1 \text{ Å}$, which corresponds to the acoustic intensity of 0.07 mW/cm² at 1.5 MHz.

A few comments on experimental configurations are worth noting. This film detector works only for pulsed acoustic wave. The deformation at one point travels at a speed of $\sqrt{T/\rho}$ ($T$: tension, $\rho$: density), which was estimated about $0.5 \times 10^4$ m/s in our case.

Fig. 2 Film holder.

Fig. 3 Test object and acoustic image.

(a) Perforated copper ring plate: The plate is composed of four groups of concentric rings in the radial direction. Inner group has two rings (rings and spaces each 3 mm) and outer three have three rings respectively (rings and spaces each 2 mm, 1 mm, and 0.5 mm).

(b) Acoustic image: Due to the limited image area, the photo is made up of two sections.
Consequently the disturbance propagates a distance of 1 mm during a pulsed excitation. On the other hand, there is a distinct advantage in the use of the heterodyne technique. As indicated above, we can measure easily the absolute value of the displacement without any other resort. So this method is suitable to the acoustic power measurement. This kind of study is now in progress at our laboratory.

References