Optical observation method for ultrasonic field using the shadowgraph introducing pulse inversion averaging

Kazuhiko Imano

Graduate School of Engineering and Resource Science, Akita University, 1–1 Tegata Gakuen-machi, Akita 010–8502, Japan

Abstract: The pulse inversion averaging (PIA) method is introduced to the shadowgraph imaging system to visualize the second-harmonic component of the ultrasonic field. The principle of the PIA method is summarized and the method is customized for observing an second-harmonic ultrasonic field. An experiment of a shadowgraph with PIA using a 1-MHz concave focused transducer is conducted to evaluate the system. The fundamental component of 1 MHz is suppressed more than 30 dB with respect to the second-harmonic component. With this system, both a normal shadowgraph image and a second-harmonic image are visualized in real time.

Keywords: shadowgraph, ultrasonic field, pulse inversion averaging, second-harmonic wave

Classification: Ultrasonic electronics

References


1 Introduction

In recent years, ultrasound has been widely used in non-destructive testing, such as medical diagnosis and flaw detection testing. In non-destructive inspection using ultrasonic waves, the measurement is performed by observing the received signal
and round trip time of the echo from the discontinuity of the acoustic characteristic impedance along the propagation path. However, actual ultrasonic wave propagation is complicated because diffraction, reflection, scattering and attenuation interact with each other. Interpretation of the field of an ultrasonic wave is important but problems are encountered when observing a sound field.

The most tentative method for observing a sound field of ultrasonic waves is to scan a miniature hydrophone in a field such as water [1]. The resulting output is directly proportional to the sound pressure of the ultrasonic wave. However, there is an essential problem that the hydrophone disturbs the sound field through the insertion of a physical sensor in the field and it cannot be used in solid material. Therefore, the development of noninvasive methods, including optical methods, is expected.

There are various optical techniques. In particular, the light diffraction method, which uses the acousto-optic effect of the interaction of light and sound, has been used as an effective means to consider the sound field. When ultrasonic waves propagate through a liquid medium, compression affects the density of the medium. As a result, there is a gradient of the refractive index of light in the medium, and light is thus modulated by ultrasound when the incident light is perpendicular to the traveling direction of the ultrasonic wave. When the incident light beam is sufficiently wide relative to the wavelength of the ultrasound, the periodic change in the gradient of the refractive index in the medium induced by ultrasonic waves serves as a diffraction grating for light. Propagation of the ultrasonic waves is thus observed as acoustically diffracted light. The Schlieren and shadowgraph methods are typical methods of visualizing an ultrasonic wave field [2]. Both methods can visualize the entire ultrasonic field in real time where light is irradiated.

Recently, the applications of second-harmonic component have been studied to obtaining high-resolution diagnostic images or to high-accuracy non-destructive inspection [3, 4]. Although the field distribution of the second-harmonic wave is important in examining acoustical or physical characteristics of material, no effective method for field observation has been developed. The second-harmonic field cannot be observed even employing the Schlieren or shadowgraph method, because those methods only visualize the fundamental wave. In medical diagnostic imaging, the pulse inversion technique has been applied to second-harmonic imaging [3]. We have developed the pulse inversion averaging (PIA) method to realize the effective detection of the second-harmonic component generated from elastic nonlinearity or nonlinear vibration at the solid contact. [4]

In this paper, a modified shadowgraph introducing the PIA method is described and an experiment using a finite-amplitude, 1-MHz focused ultrasonic wave is conducted to confirm the usefulness of the system.

2 Principle of PIA

PIA [4] has been developed for efficient detection of the second-harmonic component included in a received ultrasonic wave that has propagated through a sample. The PIA method is outlined as follows [4].
Fig. 1 shows the exciting voltage waveform for the piezoelectric transducer. A burst sine wave of several cycles of a voltage pulse of opposite phase is repeated at $T$. Here, the first pulse voltage signal $v_1(t)$ is applied to the transducer, and the second pulse $v_2(t)$ having the inverse phase of the first pulse is applied after a delay time $T$. The relation is expressed as

$$v_2(t) = -v_1(t - T),$$  \hspace{1cm} (1)

where $t$ is time. Ultrasonic pulse waves $p_1(t)$ and $p_2(t)$ corresponding to the pulse signal that radiates ultrasonic pulse waves $v_1(t)$ and $v_2(t)$ are related by

$$p_2(t) = -p_1(t - T).$$  \hspace{1cm} (2)

$p_1(t)$ and $p_2(t)$ are expressed using $v_1(t)$ and $v_2(t)$ as

$$p_1 = a_1v_1 + a_2v_2 + \cdots + a_{2k}v_{2k} + \cdots,$$  \hspace{1cm} (3)

$$p_2 = -a_1v_1 + a_2v_2 - \cdots + a_{2k}v_{2k} - a_{2k+1}v_{2k+1} + \cdots,$$  \hspace{1cm} (4)

where $a_m$ is the amplitude constant and $m$ is the order of the harmonic wave. In the process of receiving the ultrasonic pulse, $p_1(t)$ and $p_2(t)$ are averaged over a time much longer than $T$, and only the amplitudes of even order $v_{2m}$ of the pulse wave remain as

$$p_{2m} = \frac{p_1 + p_2}{2} = a_2v_2 + a_4v_4 \cdots.$$  \hspace{1cm} (5)

Thus, only the even-order components $p_{2m}$, and in particular the second-order component ($m = 1$), can be obtained because it has the highest power among the even-order components.

### 3 Observation of the sound field using the shadowgraph method with PIA

Fig. 2 shows the modified shadowgraph system with introduction of the PIA method. A sample water cell was placed between two concave mirrors. An ultrasonic concave transducer (Fuji Ceramics Co. Ltd., M-6) was fixed at the water cell and had a diameter of 30 mm, thickness of 2 mm and focal length of 30 mm. The exciting voltage signal (Fig. 1) from a function generator 1 (NF WF1974) was amplified to 150 Vpp by a bipolar amplifier (NF, HA4101A) and applied to the transducer. Pulse light (Sugawara Lab., NP-1A) having a flash time width of 70 ns...
was expanded after passing through a pinhole and mirror 1. The repetition frequency of flash was controlled by a function generator 2. Collimated light propagated in the water cell and was diffracted by the ultrasonic wave. The diffracted light was received by the CMOS digital camera (Artray ARTCAM-200CMV-USB3) after being reflected by mirror 2. In the imaging process, the exposure time of the camera was set sufficiently longer than the ultrasonic driving period $2T$ to obtain the time average of light information corresponding to the ultrasonic wave of normal and inverse phases. In the experiment, the exciting voltage was designed to be a 50-cycle, 1-MHz burst sine (with burst duration of 50 µs). After interval $T$, the next inverted exciting signal was applied to the ultrasonic transducer. In this experiment, the burst interval $T$ and the exposure time were set to 1 ms and 200 ms, respectively.

The timing of the strobe light pulse was arbitrarily controlled using a pulse delay generator (Sugawara Lab., NP-L2) with a time resolution of 10 ns; thus, a “frozen” ultrasonic field of arbitrary time can be obtained. In the sound field image, bright and dark respectively correspond to the normal and inverse phases of the wavefront when the ultrasonic wave was excited in voltage signal as in Fig. 1. Because the polarity of sound was inverted for each half wavelength, bright and dark parts canceled out in one cycle of the ultrasonic wave. Therefore, the fundamental wave was canceled out and the second-harmonic component was emphasized as in Eq. 5.

The digital data of the sound field images were transferred from the memory of the digital camera to a computer and then averaged on the computer to eliminate the noise and fluctuations of the light source. To enhance the contrast of the image, the subtraction method [5] of two images, the sound field and its background image, was employed.

Fig. 3(a) and (b) shows the ultrasonic field obtained employing the normal shadowgraph method and the shadowgraph method introducing PIA, respectively. Red and blue colors correspond to the positive and negative pressure, respectively. In Fig. 3(a), the distribution of the wavefront and the focusing of ultrasound sound can be observed in the same manner as for the conventional method. However, the second-harmonic component cannot be observed. Fig. 3(b) shows the same field obtained with the PIA method. It is seen that the interval between wavefronts is half...
that in Fig. 3(a) because the wavelengths of a fundamental frequency of 1 MHz and its second harmonic are 1.5 and 0.75 mm, respectively.

Fig. 4(a) and (b) show the magnified images around the focal points in Fig. 3(a) and (b), respectively. It is seen from Fig. 4(a) that the wavefront of the concave transducer becomes a “plane” near the focal point while the wavefronts of the upward convex and downward convex transducers are replaced before and behind the focal point as described in an earlier study [6]. In Fig. 4(b), the change in the shape of the wavefront is more gradual than that of the fundamental wavefront around the focal point. In addition, spurious and side lobe components are lowered compared to the fundamental field. The beam waist around the focal point is narrower than that of fundamental field. Fig. 5(a) and (b) shows the distribution of light intensity on the axis of the concave transducer with and without PIA, respectively. It is also clear that the spacing of the wavefront of the
second harmonic is half that of the fundamental wavefront and the light intensity is not maximized around the focal point due to the nonlinear distortion of waveform and the non-proportionality between light intensity and sound pressure in the finite amplitude field [7]. Fig. 6(a) and (b) shows the Fourier spectrum of Fig. 5(a) and (b), respectively. In Fig. 6(a), components corresponding to both fundamental and second-harmonic components are observed, where the magnitude of the fundamental component is 8 dB higher than that of the second-harmonic component. With PIA, the second-harmonic component is enhanced and becomes larger than the fundamental component by 25 dB.

As a result, relative enhancement of the second-harmonic component better than 30 dB is accomplished. The results described above demonstrate that the shadowgraph method with PIA is advantageous in observing a harmonic ultrasonic field.

4 Conclusions

In this paper, a novel method for observing an ultrasonic field including its second-harmonic component was described. It can be considered that the method is a direct way of visualizing the second-harmonic field and provides useful information for the interpretation or consideration of the ultrasonic field. The data obtained are of the intensity of light, and we will develop a system to obtain the sound-pressure amplitude and phase to quantitatively evaluate the ultrasonic field. In future work, the system will be extended using the Schlieren method or photoelectric method to visualize a finite-amplitude sound field.