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Measurement of instantaneous acoustic pressure for diagnostic ultrasound using frequency characteristics of amplitude and phase of hydrophone sensitivity

ハイドロホン感度の振幅及び位相の周波数特性を用いた
診断用超音波の瞬時音圧計測

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1. Introduction

Definition of an ultrasonic diagnostic image can be improved by increasing acoustic pressure of broadband diagnostic ultrasound, but the instantaneous acoustic pressure cannot exceed a regulatory limitation to ensure the safety of patients[1]. In order to use the instantaneous acoustic pressure as high as possible, its precise and practical measurement techniques are necessary[2].

Broadband ultrasound such as a pulse has been widely used for ultrasonic diagnostic equipment. However, measurement method for the instantaneous acoustic pressure assumed narrow-band ultrasound (here, called conventional method in the international standard[3]). For this reason, the method available to broadband ultrasound has been investigated, which uses frequency characteristics of the amplitude and phase of the hydrophone sensitivity (here, called deconvolution method[4]). At present, such measurement techniques are still under discussion mainly due to the reason that the hydrophone sensitivity is usually calibrated at discrete frequencies only and within the limited frequency range[5],[6].

In this study, firstly we introduce our new system developed for measuring the instantaneous acoustic pressure of broadband ultrasound. Then, both conventional and deconvolution methods are applied to two types of hydrophones having different frequency characteristics of the sensitivities, and the results are compared with each other.

2. Measurement method and system

In the conventional method, instantaneous acoustic pressure, $p(t)$, of ultrasound is determined as[3],

$$p(t) = \frac{u(t)}{M(f_c)}, \tag{1}$$

where $u(t)$ and $M(f_c)$ denote hydrophone output voltage and hydrophone sensitivity at center frequency, f_c, of ultrasound, respectively. As described in section 1, Eq. (1) assumes the ultrasound with approximately narrow-band, such as a tone-burst wave. On the other hand, $p(t)$ is derived using the deconvolution method as,

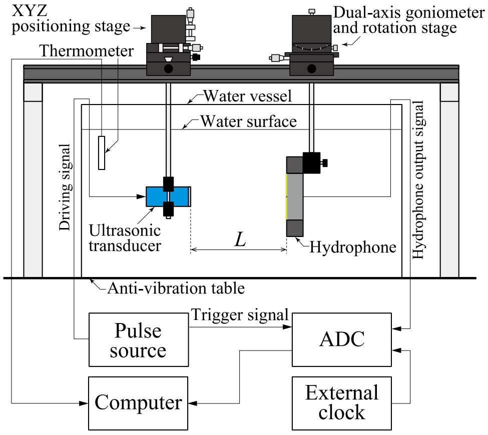

Fig. 1 Schematic diagram of experimental setup.

$$p(t) = \mathscr{F}^{-1}\left[\frac{\mathscr{F}\{u(t)\}}{M(f)}\right], \tag{2}$$

where $M(f)$ denotes frequency characteristics of the hydrophone sensitivity. Operators, $\mathscr{F}$ and $\mathscr{F}^{-1}$, indicate Fourier and inverse Fourier transforms, respectively.

Figure 1 shows a schematic diagram of experimental setup for the measurement of $p(t)$. Two types of hydrophones are a lead zirconate titanate (PZT) needle hydrophone with a 0.4 mm active element (model HNC-0400, Onda Corp.) and a polyvinylidene difluoride (PVDF) membrane hydrophone with a 0.5 mm active element (model MHB500A, NTR systems, Inc.), respectively. Ultrasonic pulse was emitted by an ultrasonic transducer (model PCS-1000, Onda Corp.). Output voltage of the hydrophone was recorded by a 12-bit analog-to-digital converter (ADC; model U1066A, Agilent Technologies, Inc.). Recording conditions of the ADC are as follows: Number of data, $N = 512$, and sampling frequency, f_s = 204.8 MHz. The sampling frequency was supplied by an external reference clock (model CK1620, NF Corp.). Distance, L, between the ultrasonic transducer and the hydrophone was set to 200 mm and determined from trigger delay time and sound velocity of distilled water in a water vessel. The sound velocity was calculated as a function of temperature, and thus water temperature was measured using a thermometer (model E640, Techonol Seven Co., Ltd.).

Figure 2 shows $M(f)$ of the two hydrophones.

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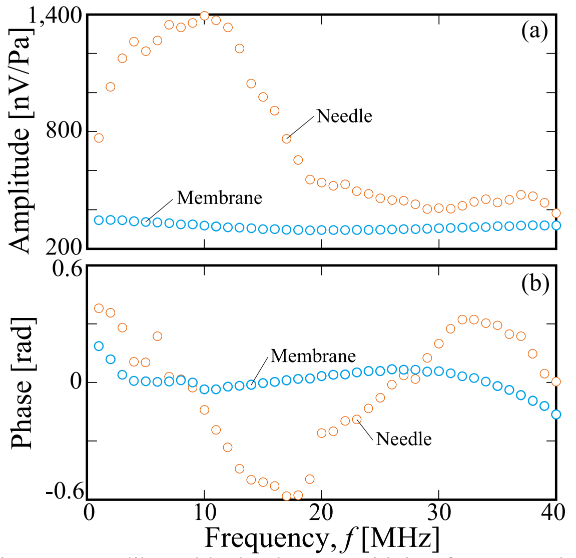

Fig. 2 Calibrated hydrophone sensitivity; frequency characteristics of (a) amplitude and (b) phase.

$M(f)$ were calibrated by the National Physics Laboratory in UK, and the range of calibration frequency was 1 to 40 MHz with 1 MHz interval. The membrane hydrophone has less frequency dependency of the amplitude and phase, compared with the needle hydrophone.

3. Results

Figure 3 shows time waveforms of instantaneous acoustic pressure, $p(t)$, using the needle and membrane hydrophones and calculated by the conventional and deconvolution methods. In order to compensate for the mismatch between the interval of calibration frequency (1MHz) and f_s/N = 0.4 MHz, the hydrophone sensitivity was interpolated linearly in the range of 1 to 40 MHz. A rectangular filter of 1 to 40 MHz was applied to $u(t)$ to delete the frequency components outside the calibration frequency range.

Comparison of Fig. 3(a) with (b) clearly indicate that the deconvolution method has good agreement of $p(t)$ between the two hydrophones, as seen in enlarged views of [i]–[iv]. Furthermore, in the deconvolution method, peak-compressionals are sharpened for the needle hydrophone and the positions of the peak-compressionals get closer for the two hydrophones. These results can be explained by the fact that each hydrophone has different frequency characteristics of the sensitivity as shown in Fig. 2, and that the deconvolution method does take frequency characteristics of the sensitivities into account. Therefore, we authors confirmed an advantage of the deconvolution method that it enables measuring the $p(t)$ of ultrasonic pulse more precisely.

4. Summary

This study showed that the instantaneous acoustic pressure obtained by the deconvolution method has

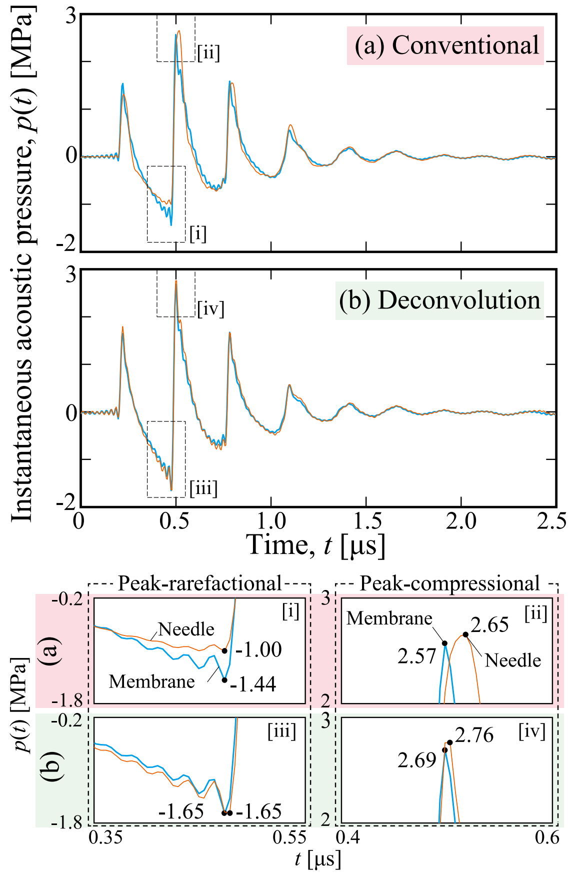

Fig. 3 Instantaneous acoustic pressure of ultrasonic pulse using needle and membrane hydrophones with 1 to 40 MHz rectangular filter; (a) conventional method, and (b) deconvolution method. Enlarged views around peak-compressional and peak-rarefactional acoustic pressure are also shown.

good agreement between the two hydrophones having different frequency characteristics of the sensitivity. In other words, this implies that the deconvolution method can reduce the uncertainty caused by the frequency dependency of the hydrophone sensitivity.

Future study includes the application of signal processing techniques for advancing the deconvolution method: Information in the original output voltage of the hydrophone was partially lost from the instantaneous acoustic pressure because the frequency components outside the range of hydrophone calibration were deleted by applying the rectangular filter. Moreover, only linear interpolation of the hydrophone sensitivity was carried out in the frequency domain to get the sensitivity not provided in the calibration certificate. Therefore, we will investigate the interpolation and extrapolation methods.

References

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