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Effect of phase frequency response of hydrophone sensitivity on instantaneous acoustic pressure of diagnostic ultrasound
診断用超音波の瞬時音圧に対するハイドロホン感度の位相周波数特性の影響

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1. Introduction

As for the specification of medical ultrasonic diagnostic equipment, the magnitude of instantaneous acoustic pressure of broadband ultrasound determines definition of a diagnostic image. However, the instantaneous acoustic pressure shall not exceed a regulatory limitation for ensuring safety of patients. In order to use the instantaneous acoustic pressure as high as possible, its precise and practical measurement techniques are required. Conventional method for measuring the instantaneous acoustic pressure assumes narrowband ultrasound[1]. Thus, methods available to broadband ultrasound have been investigated, which use frequency response of amplitude and phase on hydrophone sensitivity (here, called deconvolution method)[2-5].

Phase response of the hydrophone sensitivity is available by a few ways. Ideally, calibration certificate should be the most reliable source. In some cases, however, we might be able to regard the phase response as independent of frequency if the hydrophone has sufficiently flat frequency response. In other cases, calibration of the phase response might be replaced with theoretical calculation. The method to obtain the phase response will depend on cost and accuracy. Nevertheless, few studies have focused on the influence of the methods for determining the phase response on the instantaneous acoustic pressure quantitatively.

In this study, we investigate difference of the instantaneous acoustic pressure derived by the conventional method and the deconvolution method by three different methods for determining phase frequency response. Four hydrophones having different frequency response of the sensitivity are used and the results are compared with each other.

2. Measurement principles

Instantaneous acoustic pressure, $p(t)$, of broadband ultrasound is derived by the deconvolution method as $p(t) = \mathcal{F}^{-1}[\mathcal{F}\{u(t)\}/M(f)]$, where $u(t)$ denotes hydrophone output voltage and $M(f)$ indicates frequency response of hydrophone sensitivity ($|M(f)|$: amplitude and $\angle M(f)$: phase). Operators, $\mathcal{F}$ and $\mathcal{F}^{-1}$, denote Fourier transform and inverse Fourier transform, respectively. In the conventional method, $p(t)$ is derived as $p(t) = u(t)/|M(f_c)|$, where $|M(f_c)|$ denotes $|M(f)|$ at a center frequency, f_c, of ultrasound.

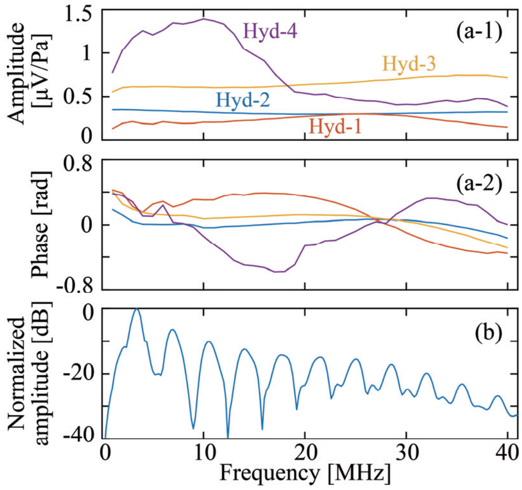

Fig. 1 Calibrated sensitivity of four hydrophones, frequency response of (a-1) amplitude and (a-2) phase, and (b) normalized spectrum amplitude of output voltage by Hyd-2 for ultrasonic pulse from ultrasonic transducer.

In this study, $p(t)$ was derived by the following methods:

- M_C: conventional method,
- M_{D0}: deconvolution method using $\angle M(f)$, assumed to be zero for all frequencies,
- M_{DB}: deconvolution method using calculated $\angle M(f)$, and,
- M_{DR}: deconvolution method using calibrated $\angle M(f)$.

In the deconvolution methods M_{D0}, M_{DB} and M_{DR}, $|M(f)|$ was obtained by calibration. In the method M_{DB}, $\angle M(f)$ was calculated by using Bode's gain-phase relation, which describes the relation between a gain and a minimum phase, $\angle M_\mathrm{m}(f)$, of a frequency transfer function[6]. By regarding $M(f)$ as the frequency transfer function and substituting $|M(f)|$ into the following equation, $\angle M(f)$ is derived as,

$$\angle M_m(f) = \frac{2f}{\pi}\int_0^\infty \frac{\ln|M(f')|/|M(f)|}{f'^2 - f^2}\,df'. \qquad (1)$$

3. Experimental method

A diagram for the measurement sytem of $p(t)$ was omitted for space saving[5]. Recording conditions of

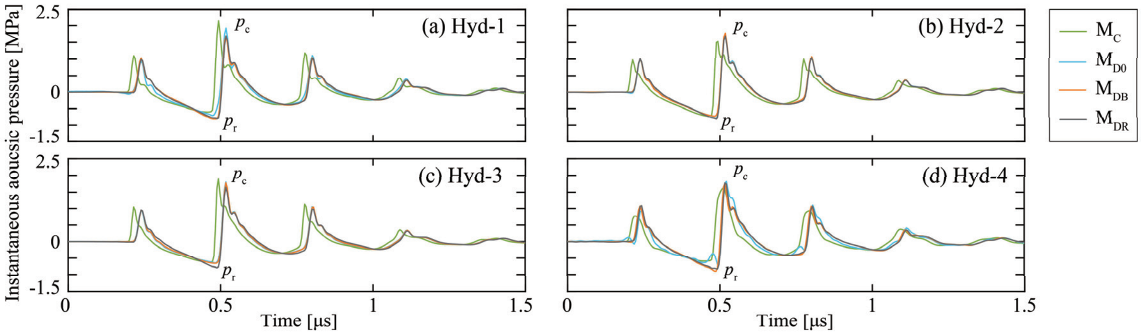

Fig. 2 Waveforms of instantaneous acoustic pressure derived by four hydrophones.

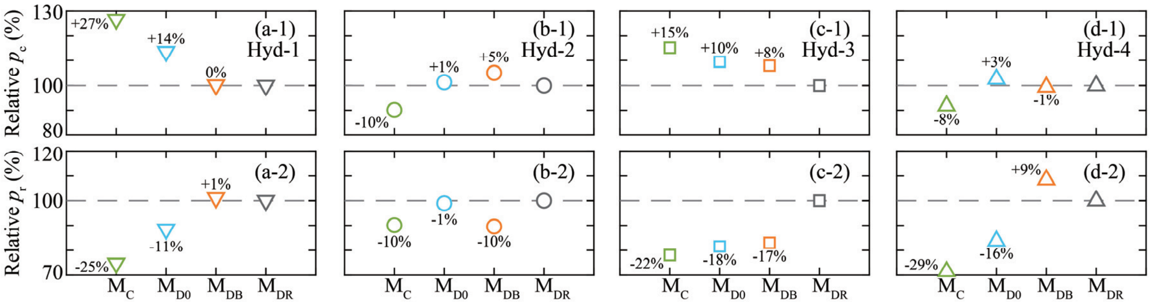

Fig. 3 Relative p_c and p_r as the ratio to the value derived by M_DR.

an analog-to-digital converter were as follows: number of samples, N = 1,024 and sampling frequency, f_s = 204.8 MHz. The instantaneous acousitc pressure was measured by using four hydrophones having different frequency response of $M(f)$. Hydrophones are Hyd-1 (HNP0400, Onda, polyvinylidene difluoride (PVDF) needle type), Hyd-2 (MHB500A, NRT Systems, PVDF membrane type), Hyd-3 (HMB0500, Onda, PVDF membrane type with backing material) and Hyd-4 (HNC0400, Onda, lead zirconate titanate (PZT) needle type), respectively. Figs. 1 (a-1) and (a-2) show $|M(f)|$ and $\angle M(f)$ calibrated by National Physical Laboratory (Teddington, UK) for each hydrophone, in the frequency range from 1 MHz to 40 MHz with an interval of 1 MHz. Fig. 1(b) shows spectrum amplitude of outpout voltage by Hyd-2 for the ultrasonic pulse from a focal ultrasonic transducer (PCS-1000, Onda, f_c = 3.4 MHz). The amplitude of spectrum was normalized by its maximum. Intervals of the spectrum is $\Delta f = f_\mathrm{s}/N$ = 0.2 MHz.

The deconvolution method requires signal processing techniques such as interpolation and extrapolation of $M(f)$, and filtering of $p(t)$. In this study, the extrapolation followed the way by Hurrell *et al*[3]. In addition, we applied spline interpolation and seventh-order lowpass Butterworth filter, which were also proposed by Hurrell *et al*[3]. Cutoff frequency of the filter was set to 35 MHz for all hydrophones.

4. Results

Fig. 2 shows waveforms of $p(t)$ derived by each method for four hydrophones. In Fig. 2, however, it is not easy to compare each peak-compressional pressure, p_c, and peak-rarefactional pressure, p_r, among the four method M_C, M_D0, M_DB and M_DR in detail. Thus, Fig. 3 was additionally introduced.

Fig. 3 consists of diagrams on p_c (upper) and p_r (lower) for four hydrophones. Each diagram shows dependency of p_c or p_r on the method for determining $\angle M(f)$ and this dependency was indicated as a ratio to the value by M_DR. For specific combination of the ultrasonic transducer and four hydrophones, each ratio of p_c and p_r ranges for four hydrophones as follows: -10% to +27% (p_c) and -29% to -10% (p_r) in M_C, +1% to +14% (p_c) and -18% to -1% (p_r) in M_D0 and -1% to +8% (p_c) and -17% to +9% (p_r) in M_DB. p_c and p_r in M_DR are always equal to zero because they were used as reference values. Fig. 3 shows that p_c and p_r obtained by three hydrophones (Hyd-1, 3 and 4) tend to approach the corresponding values in M_DR in the order of M_C, M_D0 and M_DB. However, Hyd-2 is exceptional and p_c and p_r in M_D0 are close to the values in M_DR compared with M_DB.

5. Summary

We confirmed that peak-compressional pressure and peak-rarefactional pressure are significantly influenced by the method for determining phase frequency response of hydrophone sensitivity.

In the future, we will apply the other ultrasonic transducers having different frequency response for further discussion.

References

1. IEC 62127-1 Ed. 1.1:2013.
2. K. A. Wear *et al.*: IEEE UFFC **61**, 62 (2014).
3. A. M. Hurrell and S. Rajagopal: IEEE UFFC **64**, 126 (2017).
4. M. Weber and V. Wilkens: Proc. 2017 IEEE Ultrason. Symp., (2017).
5. Y. Chiba *et al.*: Proc. Symp. Ultrason. Electr. **39**, 1P5-7 (2018).
6. L. A. Zadeh and C. A. Desoer: *Linear System Theory* (McGraw-Hill, NY, 1963) p. 434.