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Effect of extrapolation of frequency-dependent 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周波数特性の外挿の影響

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1. Introduction

Brightness of a diagnostic image can be improved by increasing the instantaneous acoustic pressure of broadband ultrasound. However, the magnitude of the ultrasound radiated from a diagnostic equipment is limited for ensuring the safety of patients. In order to use instantaneous acoustic pressure as high as possible, its precise and practical technique is required. Thus, a method available to broadband ultrasound has been investigated, which use frequency response of hydrophone sensitivity (hereinafter, called deconvolution method). [1–4]

A bandwidth of diagnostic ultrasound is often wider than a frequency range of certificated sensitivity. In this kind of situation, an extrapolation to the frequency response of hydrophone sensitivity is expected to be an effective approach to implement the deconvolution method (hereinafter, called extrapolation treatment). However, few studies have focused on the extrapolation technique.

Another approach is to apply a bandpass filter to an output voltage by a hydrophone detecting ultrasound in order to cut frequencies out of the range of sensitivities (hereinafter, called filtering treatment). When the hydrophone sensitivities with sufficiently broad frequency ranges are given, the filtering treatment is available for the deconvolution method as treated in many previous researches.[2–4]

In the present study, we investigate frequency ranges of certificated hydrophone sensitivities which are necessary for precise measurements of instantaneous acoustic pressure using extrapolation and filtering treatments. Four hydrophones having different frequency-dependent sensitivity are used, and results are compared with each other.

2. Measurement principle and experimental method

Instantaneous acoustic pressure $p(t)$, of ultrasonic pulse is derived by the deconvolution method as $p(t) = \mathcal{F}^{-1}[\mathcal{F}\{u(t)\}/K(f)]$ where $u(t)$ denotes hydrophone output voltage and $K(f)$ indicates the frequency-dependent hydrophone sensitivity. Operators, $\mathcal{F}$ and $\mathcal{F}^{-1}$, indicate Fourier transform and inverse Fourier transform, respectively.

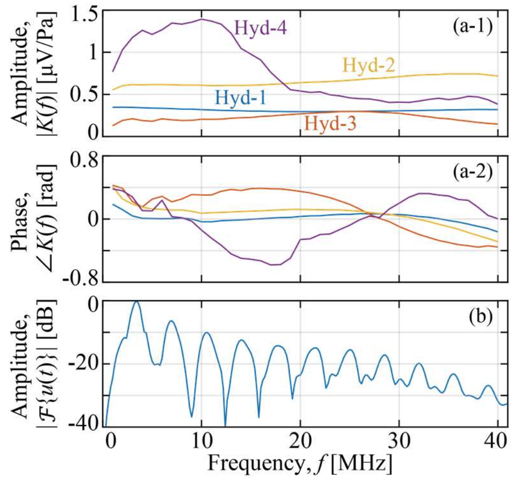

Fig. 1. (a) Certificated sensitivity of four hydrophones; frequency dependency of (a-1) amplitude and (a-2) phase. (b) normalized spectrum amplitude of output voltage by Hyd-1 for ultrasonic pulse from ultrasonic transducer.

A diagram for measurement system of $p(t)$ was omitted due to space limitation.[4] We used four hydrophones (Hyd) for measuring $p(t)$. **Figure 1**(a) shows certificated frequency-dependent $K(f)$ of Hyd-1 through Hyd-4, in the frequency range from 1 MHz to 40 MHz. In Figs. 1(a-1) and 1(a-2), Hyd-1 through Hyd-4 denote membrane type (model MHB500A, NTR Systems), membrane type (model HMB0500, Onda), needle type (model HNP0400, Onda), and, needle type (model HNC0400, Onda), respectively. We used a focal transducer with a pulse generator (model PCS-1000, Onda; nominal focal length 95 mm). Figure 1(b) shows the amplitude spectrum of the waveform measured by Hyd-1 at the position of 180 mm from the front of the transducer (center frequency, $f_c = 3.4$ MHz). The amplitude of spectrum was normalized by its maximum. The output voltage was recorded by an analog-to-digital converter. Recording conditions were as follows: sampling frequency, f_s = 204.8 MHz, and the number of data points, $N = 1024$.

In the present study, the same signal processing for the deconvolution method to derive

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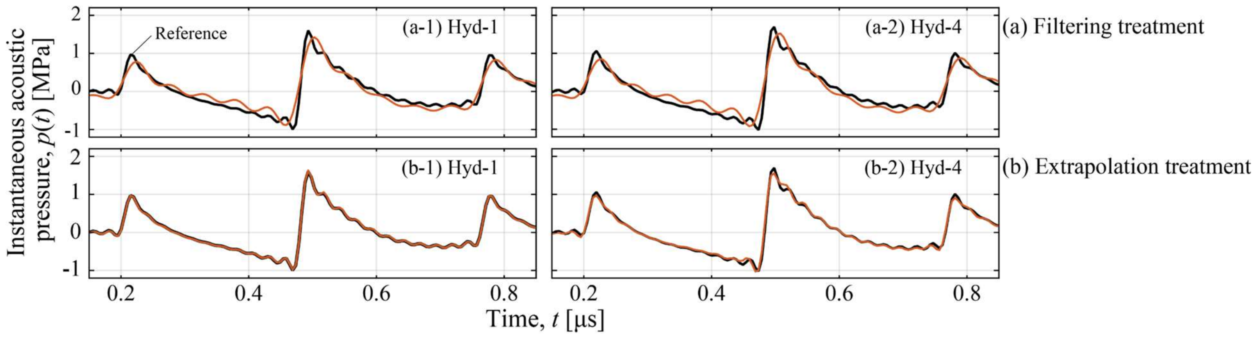

Fig. 2. Time waveforms of $p(t)$ measured by Hyd-1 (membrane type) and Hyd-4 (needle type); derived by (a) Filtering and (b) Extrapolation treatments. Frequency range in which certificated hydrophone sensitivities are given is from f_L = 2.4 MHz to f_H = 20 MHz.

Table I. Narrowest frequency ranges from f_L to f_H when difference of positive and negative temporal peak acoustic pressures of $p(t)$ from those pressures of reference waveforms are both within ±10%.

	(a) Filtering treatment			(b) Extrapolation treatment		
	f_L [MHz]	f_H [MHz]	$f_H - f_L$ [MHz]	f_L [MHz]	f_H [MHz]	$f_H - f_L$ [MHz]
Hyd-1 (membrane)	2.0	18.8	16.8	2.8	3.4	0.6
Hyd-2 (membrane)	2.4	18.3	15.9	3.4	3.4	0
Hyd-3 (needle)	2.4	17.8	15.4	1.0	20.7	19.7
Hyd-4 (needle)	2.3	18.0	15.7	3.4	19.5	16.1

instantaneous acoustic pressure was used as in Ref. 5, except to use a rectangular filter. In the filtering treatment, the pass band of the filter to the output voltage by each hydrophone is equalized to a frequency range in which certificated sensitivities are given. The frequency range varies in the present study, from f_L = 1 MHz to f_H = 40 MHz in the broadest case and nothing other than $f_L = f_H = f_c$ in the narrowest case.

In the extrapolation treatment, the pass band of the filter is fixed from 1 MHz to 40 MHz. The frequency range from f_L to f_H varies the same as the filtering treatment. Outside of the frequency range, the frequency response of each hydrophone sensitivity is extrapolated. Constants $K(f_L)$ and $K(f_H)$ are applied on lower and higher outsides of the frequency range, respectively.

$p(t)$ derived using the filtering treatment in the case of f_L = 1 MHz and f_H = 40 MHz is set as the reference waveform for each hydrophone because all certificated sensitivities are given for the derivation. Other $p(t)$ derived using fewer certificated sensitivities in filtering and extrapolation treatments are compared with the reference waveform in the present study.

3. Results

Figure 2 exemplifies time waveforms of $p(t)$ (displayed as red solid lines) derived using filtering and extrapolation treatments in the case of f_L = 2.4 MHz and f_H = 20 MHz for Hyd-1 and Hyd-4, and their reference waveforms (displayed as black solid lines). Waveforms derived using the extrapolation treatment shown in Figs. 2(b-1) and 2(b-2) are in good agreement with each reference waveforms better than those using the filtering treatment in Figs. 2(a-1) and 2(a-2).

Table I shows the narrowest frequency ranges from f_L to f_H when the difference of positive and negative temporal peak acoustic pressures derived using filtering and extrapolation treatments from those pressures of reference waveforms are both within ±10%. The frequency range for the extrapolation treatment is narrower than that for the filtering treatment for Hyd-1 and Hyd-2 which have relatively flat frequency responses. This means that temporal peak acoustic pressures can be measured using fewer certificated hydrophone sensitivities by the extrapolation treatment than the filtering treatment. On the other hand, for Hyd-3 and Hyd-4 with large fluctuations in frequency responses of sensitivities, the simple extrapolation to frequency responses using constants does not seem appropriate to compensate a lack of certificated sensitivities.

4. Summary

It is confirmed that a precise waveform of instantaneous acoustic pressure is obtained by an application of extrapolation treatment on instantaneous acoustic pressure measurement using deconvolution method when a bandwidth of ultrasound is wider than a frequency range of certificated hydrophone sensitivity. We intend to investigate further an effect of the extrapolation treatment on temporal peak pressure measurement which is important for an evaluation of ultrasonic diagnostic equipment.

References

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