Comparison of Three Different Transducer Concepts for Acoustic Bladder Volume Measurements

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***Abstract* - In a preceding study the importance of noninvasive bladder volume measurements was addressed, and a new technique to measure the bladder volume on the basis of nonlinear ultrasound wave propagation was validated. It was shown that the harmonic level generated at the posterior bladder wall increases for larger bladder volumes. The objective of this study is to design an optimal transducer to implement this approach. For this purpose, three different transducer concepts, i.e. a multi-layer transducer, a broadband piezo-composite transducer and a multi-element transducer, were mutually compared using calibrated hydrophone measurements in water and pulse-echo measurements on a bladder test phantom. The effects of an additional acoustic lens on the beamwidth and generated peak pressures were also considered.**

Keywords – acoustic lens; multi-layer; piezo-composite; multi-element; nonlinear wave propagation; bladder volume

I. Introduction

In a preceding study a new technique to noninvasively measure the bladder volume on the basis of nonlinear ultrasound wave propagation was described [1]. It uses the medium-specific relationship between the nonlinearity and the attenuation of the acoustic wave propagation, reflected in the so-called "Gol'dberg number" [1], to differentiate between urine and tissue. Given a much stronger nonlinear behavior for urine than for tissue, it should be possible to find a relationship between the amount of generated harmonics present within echoes received from a Region of Interest (ROI) behind the posterior bladder wall and the amount of urine present within the propagation path (Fig 1). A dedicated transducer is needed to implement this approach. Therefore, the objective of this study is to design an optimal transducer with respect to the transmission and reception sensitivity and beamforming.

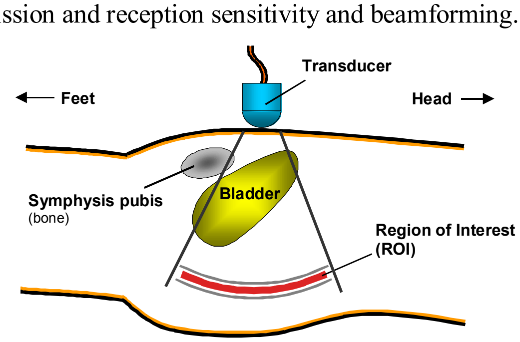


Figure 1. Set-up for bladder volume measurements on the basis of nonlinear wave propagation.

Three different transducer concepts were mutually compared using calibrated hydrophone measurements and pulse-echo measurements. As a design criterion, the transmit sensitivity at fundamental frequency should be such that the generated second harmonic peak pressure due to non-linear propagation in water is at least 40 kPa at an axial distance of 120 mm. Further, the –6 dB beamwidth at 120 mm should be at least 60 mm to capture a large part of the bladder. With respect to the beamforming, the ultrasound field should be as homogeneous as possible to avoid weighting of the volume due to the field directivity.

II. Materials and Methods

Three different transducer concepts were compared (Fig 2):

1) An unfocused multi-layer transducer [2] with active diameter of 29 mm, using a single element PZT-transducer (model A397S, GE Panametrics, USA), with 2 MHz center frequency and -6 dB BW of 55%, for transmission, and a 52 µm thick PVDF top-layer (Measurement Specialties Inc., USA) for reception.

2) An unfocused broadband single element 1-3 piezo-composite transducer (Imasonic, Besançon, France) with active diameter of 29 mm, designed for optimal transmission at 2.25 MHz and reception of the fundamental, second and third harmonics with fractional bandwidths of 10%.

3) An unfocused multi-element transducer consisting of an air-backed PZT ring-element (PXE 5, Morgan Morgan Electro Ceramics B.V., the Netherlands) with outer radius of 10 mm and inner radius of 5 mm for transmission at 2.2 MHz, and a broadband unfocused PZT inner-element with active radius of 5 mm for reception (4.5 MHz center frequency, -6 dB BW: 61%).

All three concepts were mutually compared using calibrated hydrophone measurements in water. The measurements were performed, with and without an additional acoustic lens made of Rexolite (Goodfellow Cambridge Ltd., UK) with a radius of curvature (ROC) of 35 mm. This lens is used to obtain a diverging acoustic beam (Fig 1). The lens material properties are given in table 1. Pulse-echo measurements on a bladder test phantom were performed, without the acoustic lens attached, to compare the reception sensitivities.

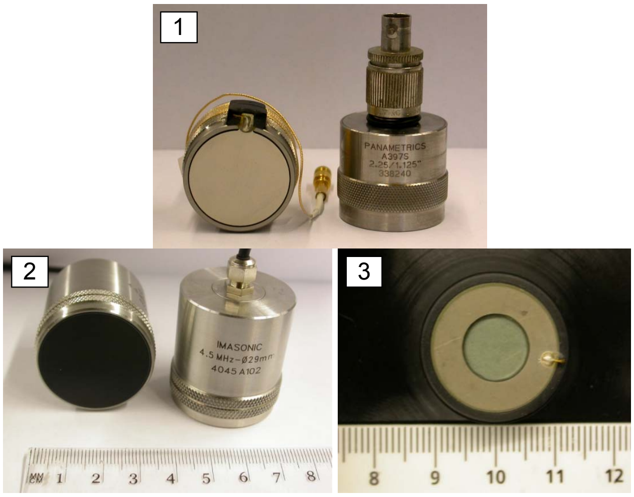


Figure 2. The three different transducer concepts.

TABLE I. LENS MATERIAL (REXOLITE) PROPERTIES OBTAINED FROM LITERATURE AND MEASUREMENTS.

	Density (g/cm³)	Sound speed (m/s)	Acoustic impedance (MRayl)	Transm. coefficient	Acoustic loss (dB/(mm·MHz))
Literature*	1.06	2340	2.57	-	0.0367
Measured	1.05	2225	2.33	0.95	0.0370

*Obtained from H. Wang et al. [3]

All transducers were excited with a Gaussian modulated 15-cycle sinewave burst with center frequency equal to that of the transducer concept under investigation. To be able to compare the transmit sensitivities, the drive level was set at 200 Vpp. To avoid the presence of harmonic components in the transmitted signal, a passive 9^{th} order Butterworth low-pass filter with cut-off frequency of 2.5 MHz was used between the transducer and the used power amplifier.

A. Calibrated hydrophone measurements.

Calibrated hydrophone measurements were performed in water using a needle hydrophone with active diameter of 200 µm (Precision Acoustics Ltd., UK) to measure the lateral pressure distributions at an axial distance of 120 mm. A total lateral distance of 160 mm was scanned with step size of 2 mm. The hydrophone measurements were performed with and without the additional acoustic lens to observe the effects on the lateral beamwidth and generated peak pressures.

Data-acquisition was performed with a digital oscilloscope (LeCroy model 9400A, LeCroy Corp., USA) with sampling frequency of 100 MHz and an 8-bit A-to-D converter. Data were transferred to a PC using a GPIB interface. A total of 30 RF-traces were averaged for each recording. The recordings were then band-pass filtered at the fundamental, the 2^{nd} harmonic and 3^{rd} harmonic frequencies. The maximum values of these bandpass-filtered signals were plotted to obtain the lateral pressure distributions for each of the frequency components.

B. Pulse-echo measurements on a bladder test phantom.

Pulse-echo measurements were performed on a bladder test phantom to compare the receive sensitivities of the three concepts. B-mode images were obtained by mechanically moving the transducers, without the lens, across the phantom with a step size of 2 mm. The same excitation was used as with the hydrophone measurements.

Data-acquisition was now performed with a PC oscilloscope (Handyscope 3, Tiepie Engineering, the Netherlands) with sampling frequency of 50 MHz and a 12-bit A-to-D converter. Data were transferred to a PC using a USB 2.0 interface. A total of 100 RF-traces were now averaged for each recording, and band-pass filtered at the fundamental, the 2^{nd} harmonic and 3^{rd} harmonic frequencies. The envelopes of these bandpass-filtered signals were then plotted as B-mode images for each frequency component.

III. RESULTS

A. Calibrated hydrophone measurements.

The results of the hydrophone measurements in water are shown in Fig 3 and Fig 4. The plots are normalized to a pressure of 1 MPa. As the multi-layer and the composite transducers showed similar pressure distributions, only the results of the piezo-composite transducer are shown in Fig 3.

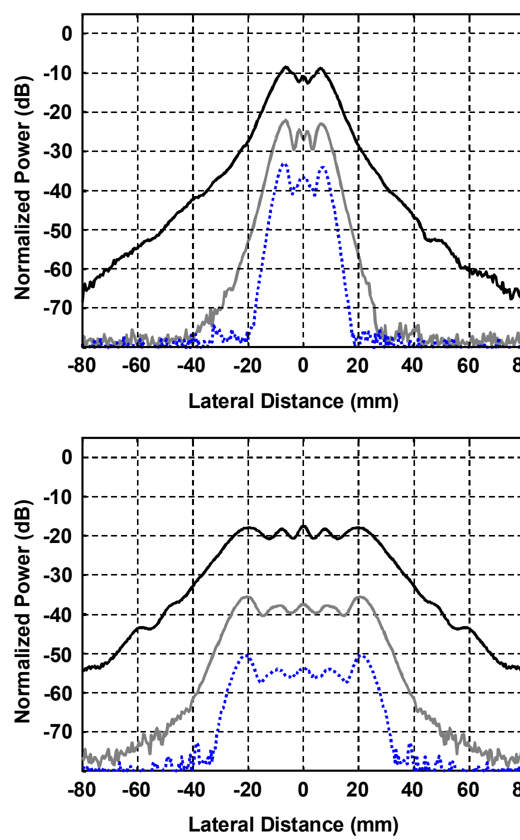
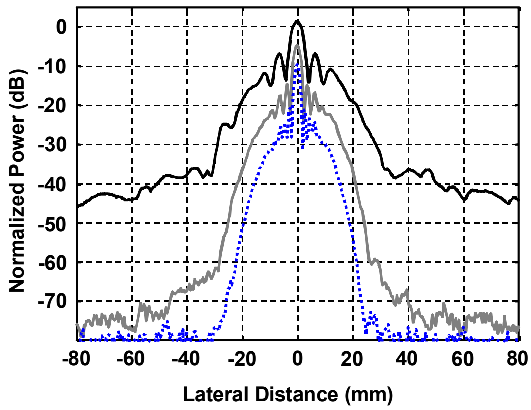


Figure 3. Measured lateral pressure distributions, at axial distance of 120 mm, representable for the first two transducer concepts, without (top) and with (bottom) acoustic lens (with ROC of 35 mm) applied. The black lines represent the distributions for the fundamental frequency. The gray and dotted lines represent the distributions for the 2^{nd} and 3^{rd} harmonics, respectively.



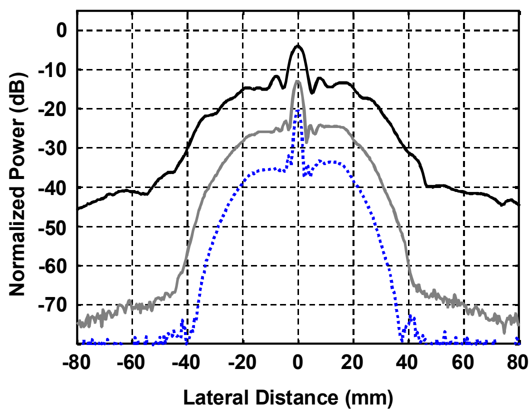


Figure 4. Measured lateral pressure distributions, at axial distance of 120 mm, for the multi-element transducer concept, without (top) and with (bottom) acoustic lens (with ROC of 35 mm) applied. The black lines represent the distributions for the fundamental frequency. The gray and dotted lines represent the distributions for the 2nd and 3rd harmonics, respectively.

A summary on the measured peak pressures and lateral beamwidths is given in tables 2 and 3. The multi-element transducer clearly generates the highest pressures, but has a very narrow –6 dB beamwidth, even with an acoustic lens applied. The design requirement of 60 mm is met when the –20 dB beamwidth is considered. However, the large on-axis sensitivity, which is typical for a concentric ring element, introduces an unwanted weighting of the volume present within the beam. The –6 dB beamwidth increased from 25 mm to 60 mm when the acoustic lens was applied on the first two concepts. The fundamental and second harmonic pressures decreased with 8 dB and 13 dB, respectively, for both transducers. Unlike with the multi-element transducer, the pressure distributions obtained with these concepts are homogeneous.

B. Pulse-echo measurements on a bladder test phantom.

Fig. 5-7 show the B-mode images obtained from the bladder phantom. In this case the acoustic lens was not applied. All concepts allow for 2nd harmonic imaging with sufficient SNR. The multi-element transducer also allows for 3rd harmonic imaging and shows better lateral resolution due to the narrow beamwidth (see Fig 4.). The images clearly show the presence of harmonics behind the cavity and the absence of harmonics when no cavity is present, illustrating the principle of the new volume measurement technique.

TABLE II. RESULTS OF THE CALIBRATED HYDROPHONE MEASUREMENTS, WITHOUT ACOUSTIC LENS APPLIED.

	Fund. (MPa)	2nd Harm. (kPa)	3rd Harm. (kPa)	-6 dB Beamwidth (mm)
Multi-layer	0.39	77	20	26
Composite	0.36	70	20	23
Multi-element	1.14	570	330	5.5

TABLE III. RESULTS OF THE CALIBRATED HYDROPHONE MEASUREMENTS, WITH ACOUSTIC LENS APPLIED.

	Fund. (MPa)	2nd Harm. (kPa)	3rd Harm. (kPa)	-6 dB Beamwidth (mm)
Multi-layer	0.17	22	4	62
Composite	0.13	16	3	59
Multi-element	0.62	225	95	6.8

IV. CONCLUSIONS AND DISCUSSION

The results showed that the multi-element concept has the best transmission and reception sensitivity. However, even with an acoustic lens, it has a very narrow –6 dB beamwidth, which is typical for a concentric ring transducer. Although the –20 dB beamwidth is sufficient, an unwanted strong on-axis sensitivity is present. Also, its relatively small active area should be put in perspective with the other concepts. Therefore, the multi-element concept with a concentric ring element is not favorable for bladder volume measurements.

The other two concepts do meet the beamwidth requirements. From the B-mode images, the piezo-composite transducer showed to have excellent sensitivity in reception. In transmission however, it is the least sensitive of the three concepts. The multi-layer concept performs slightly better in transmission than the piezo-composite transducer, but the PVDF-layer reception sensitivity is relatively low and suffers from electronic noise. The design of the multi-layer concept does allow for significant improvements in the transmission and the reception sensitivity, and is therefore preferred for bladder volume measurements above the other two concepts.

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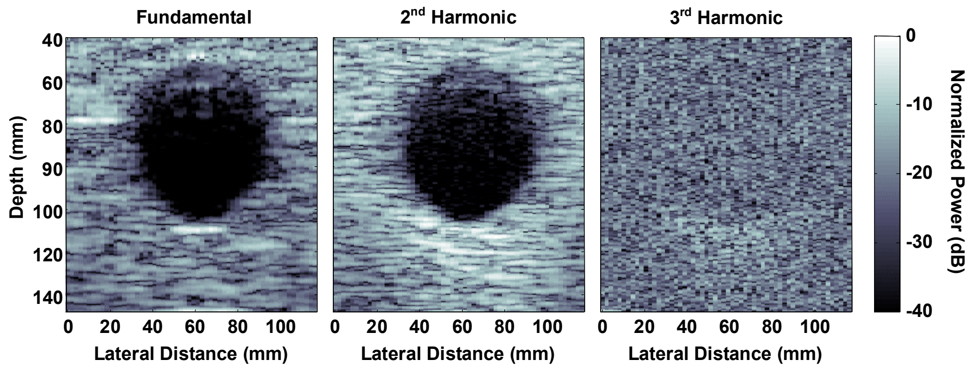

Figure 5. B-Mode images obtained from mechanically moving the multi-layer transducer, without the acoustic lens applied, across a bladder phantom with volume of 500 ml., with step size of 2 mm. The acquired data were filtered to obtain images at the fundamental, 2nd harmonic and 3rd harmonic frequencies

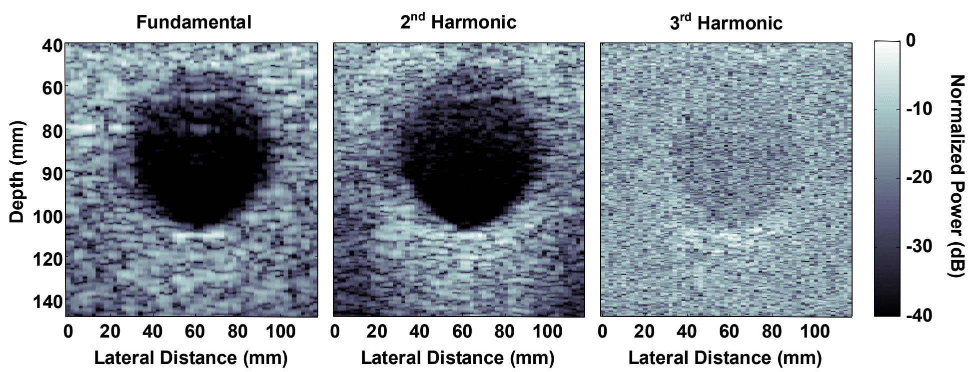

Figure 6. B-Mode images obtained from mechanically moving the piezo-composite transducer, without the acoustic lens applied, across a bladder phantom with volume of 500 ml., with step size of 2 mm. The acquired data were filtered to obtain images at the fundamental, 2nd harmonic and 3rd harmonic frequencies.

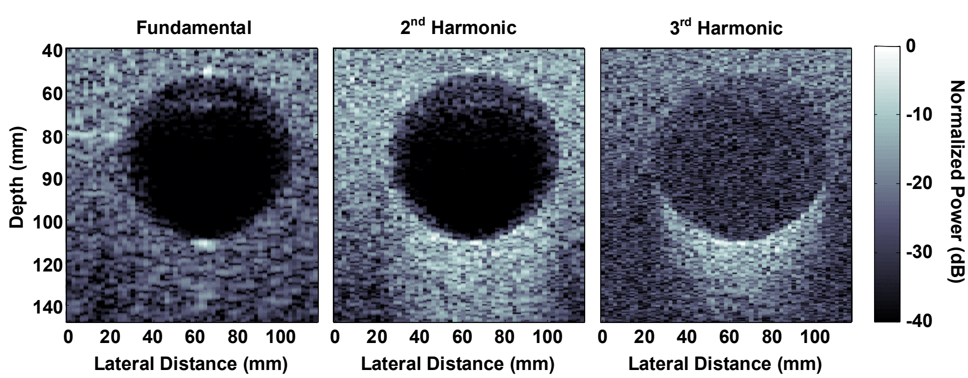

Figure 7. B-Mode images obtained from mechanically moving the multi-element transducer, without the acoustic lens applied, across a bladder phantom with volume of 500 ml., with step size of 2 mm. The acquired data were filtered to obtain images at the fundamental, 2nd harmonic and 3rd harmonic frequencies.