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Transfer functions of US transducers for harmonic imaging and bubble responses

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Abstract

Current medical diagnostic echo systems are mostly using harmonic imaging. This means that a fundamental frequency (e.g., 2 MHz) is transmitted and the reflected and scattered higher harmonics (e.g., 4 and 6 MHz), produced by nonlinear propagation, are recorded. The signal level of these harmonics is usually low and a well-defined transfer function of the receiving transducer is required. Studying the acoustic response of a single contrast bubble, which has an amplitude in the order of a few Pascal, is another area where an optimal receive transfer function is important.

We have developed three methods to determine the absolute transfer function of a transducer. The first is based on a well-defined wave generated by a calibrated source in the far field. The receiving transducer receives the calibrated wave and from this the transfer functions can be calculated. The second and third methods are based on the reciprocity of the transducer. The second utilizes a calibrated hydrophone to measure the transmitted field. In the third method, a pulse is transmitted by the transducer, which impinges on a reflector and is received again by the same transducer. In both methods, the response combined with the transducer impedance and beam profiles enables the calculation of the transfer function.

The proposed methods are useful to select the optimal piezoelectric material (PZT, single crystal) for transducers used in reception only, such as in certain 3D scanning designs and superharmonic imaging, and for selected experiments like single bubble behavior.

We tested and compared these methods on two unfocused single element transducers, one commercially available (radius 6.35 mm, centre frequency 2.25 MHz) the other custom built (radius 0.75 mm, centre frequency 4.3 MHz). The methods were accurate to within 15%.

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Keywords: Transducer; Transfer function; Efficiency; Sensitivity; Reciprocity

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1. Introduction

Harmonic imaging is an established technique used in current medical diagnostic echo systems [1]. A fundamental frequency (e.g., 2 MHz) is transmitted into the human body and the reflected higher harmonics (e.g., 4 and 6 MHz), produced by nonlinear propagation, are recorded. The signal level of these harmonics is low [1] and as such the efficiency in both transmission and reception and bandwidth of the transducer are critical. An area where an optimal transfer function in reception is important, is the study involving the acoustic response of single contrast bubbles, which are in the order of a few Pascal.

To assess the performance of a transducer absolute measurements of its transfer functions are important. The

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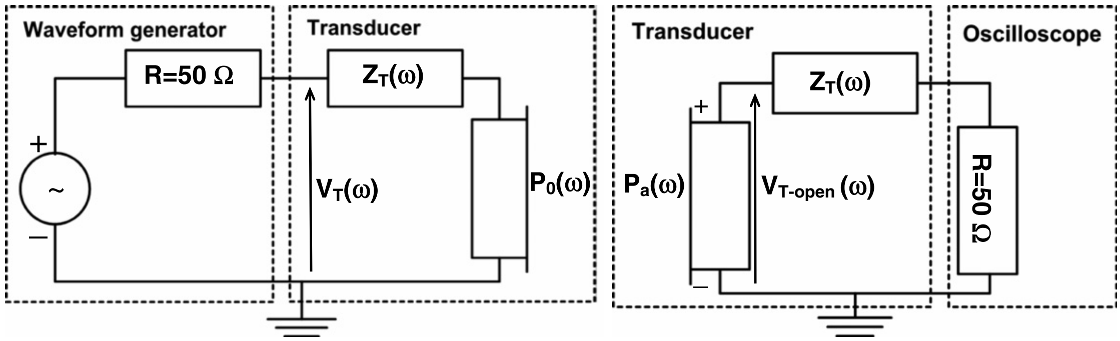

Fig. 1. The essentials of the transmission and receive circuits are shown schematically on the left and right, respectively.

functions of importance are the transmit, receive and pulse-echo transfer functions. In general, to characterize a transducer the transmit transfer function is measured using a hydrophone. Also pulse-echo measurements are standard. Receive transfer functions are generally not considered. In this article we show that if one of the three transfer functions is measured the other two can be derived, if in addition the impedance of the transducer is measured.

We have adapted and tested three methods to determine absolute transfer functions, which are independent of the circuitry connected to the transducer. In the next section the necessary theory will be established.

2. Theory

The transducer transmit efficiency ($S_T(\omega,z)$) is defined by the International Electrotechnical Commission (IEC) as [2]

$$S_T(\omega,z) = \frac{|p(\omega,z)| \cdot z}{|I_T(\omega)|}, \tag{1}$$

where $p(\omega,z)$ is the acoustical point pressure at an axial distance z of the transducer, ω is the angular frequency and $I_T(\omega)$ is the current through the transducer.

For unfocused transducers a reference transmit efficiency $S_{\text{ref}}(\omega)$ can be defined as the transmit efficiency in the far field, whereas for focused transducers the reference transmit efficiency is defined to be the transmit efficiency at the focal point.

By rewriting expressions reported by Chen et al. [3] $|p(\omega,z)|$ can be expressed as a function of $|p_0(\omega)|$ at the reference position

$$|p(\omega,z)| = \frac{A_T}{\lambda \cdot z}|p_0(\omega)|, \tag{2}$$

where A_T is the transducer surface area and λ the wave length.

Combining (1) and (2) yields

$$|p_0(\omega)| = \frac{\lambda}{A_T} S_{\text{ref}}(\omega) \cdot |I_T(\omega)|. \tag{3}$$

The transducer transmit transfer function ($T_{\text{transmit}}(\omega)$) is defined to be

$$T_{\text{transmit}}(\omega) = \frac{|p_0(\omega)|}{|V_T(\omega)|}, \tag{4}$$

where $V_T(\omega)$ is the voltage over the transducer (see Fig. 1).

Combining (3) and (4) produces

$$T_{\text{transmit}}(\omega) = \frac{1}{|Z_T(\omega)|} \cdot \frac{\lambda}{A_T} S_{\text{ref}}(\omega), \tag{5}$$

where $Z_T(\omega)$ is the complex impedance of the transducer.

The receive transfer function ($T_{\text{receive}}(\omega)$) is defined to be similar to the sensitivity in reception ($M_T(\omega)$) as defined by the IEC [2]

$$M_T(\omega) = T_{\text{receive}}(\omega) = \frac{|V_{T\text{-open}}(\omega)|}{|p_a(\omega)|}, \tag{6}$$

where $V_{T\text{-open}}(\omega)$ is the open circuit voltage over the transducer (see Fig. 1) and $p_a(\omega)$ the received pressure averaged across the transducer surface.

2.1. Reciprocity

The spherical wave reciprocity parameter J for transducers of arbitrary shape and size is given by Bobber [4]

$$J(\omega) = \frac{M_T(\omega)}{S_{\text{ref}}(\omega)} = \frac{2}{\rho \cdot f}, \tag{7}$$

where ρ is the density of the medium in which the transducer is inserted and f the frequency.

A relation between $T_{\text{transmit}}(\omega)$ and $T_{\text{receive}}(\omega)$ is obtained by combining (5)–(7)

$$\frac{T_{\text{receive}}(\omega)}{T_{\text{transmit}}(\omega)} = \frac{2 \cdot |Z_T(\omega)| \cdot A_T}{\rho \cdot c_0}, \tag{8}$$

where c_0 is the acoustic wave speed of the medium in which the transducer is inserted.

3. Method

3.1. Experimental setup

The experimental setup consisted of a tank filled with water with the transmitting transducer mounted in the sidewall and the receiving transducer, hydrophone or flat

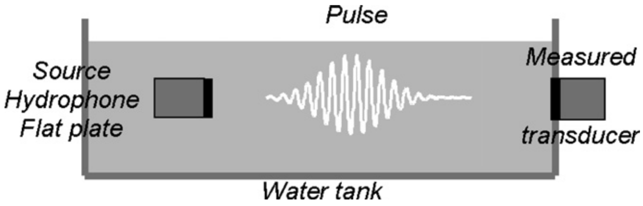

Fig. 2. Schematic diagram of the experimental setup.

plate mounted in a holder controlled by an *xyz*-system (see Fig. 2).

Care was taken to ensure that the transmitter output pressure was of such low magnitude that nonlinear propagation could be neglected. The influence of attenuation was neglected as well, as the propagation distance in water was small, in the order of centimetres. A correction for diffraction is necessary to recalculate the pressure at the transducer surface from a pressure measured some distance away. The exact diffraction correction function posted by Goldstein et al. [5] is used to correct for the diffraction effects of a transmitting flat, circular piston transducer mounted in an infinite rigid baffle and the spatial averaging effects by a receiving flat circular piston transducer in a coaxial geometry. The expression given by Chen and Schwarz [6] is used to correct for the diffraction of a flat plate transducer to a flat plate (perfect reflector) and back to the transducer. As a transmission pulse a spike was generally used.

3.2. Direct transmit transfer measurement

The transducer is mounted in the sidewall of the tank and used as a source transmitting a known pulse. A hydrophone is mounted in the holder of the *xyz*-system and measures the transmitted field. The transmit transfer function (T_{transmit}) of the transmitting transducer is calculated by

$$T_{\text{transmit}} = \frac{V_{\text{hydr}}}{V_{\text{transmit}}} \cdot \frac{1}{T_{\text{hydr}} \cdot D_{\text{transmit}}}, \tag{9}$$

where V_{hydr} is the Fourier transformed voltage produced by the hydrophone, V_{transmit} the Fourier transformed voltage measured over the impedance of the transmitting transducer, T_{hydr} the hydrophone transfer function and D_{transmit} the diffraction correction function for the transmitting transducer.

3.3. Direct receive transfer measurement

A source with known transmit transfer function is mounted in the sidewall of the tank transmitting a known pulse. The transducer is mounted in the holder of an *xyz*-system and used as a receiver. Its receive transfer function (T_{receive}) is calculated by

$$T_{\text{receive}} = \frac{V_{\text{T-open}}}{V^{\text{source}}_{\text{transmit}}} \cdot \frac{1}{T^{\text{source}}_{\text{transmit}} \cdot D^{\text{source}}_{\text{transmit}}}, \tag{10}$$

where $V_{\text{T-open}}$ is the Fourier transformed open circuit voltage produced by the receiving transducer, V_{transmit} the Fourier transformed voltage measured over the source impedance, T_{transmit} the transmit transfer function of the source and D_{transmit} the diffraction correction function for the source.

3.4. Pulse-echo

The transducer is mounted in the sidewall of the tank. It transmits a known pulse, which impinges on a thick aluminium plate reflector. The same transducer receives the reflected sound. The transmit and receive transfer functions of said transducer are related by

$$T_{\text{transmit}} \cdot T_{\text{receive}} = \frac{V_{\text{T-open}}}{V_{\text{transmit}}} \cdot \frac{1}{D \cdot R_{\text{reflector}}}, \tag{11}$$

where $V_{\text{T-open}}$ is the Fourier transformed open circuit voltage produced in reception, V_{transmit} the Fourier transformed voltage measured over the transducer impedance in transmission, D the diffraction correction function for the transmitting transducer to the flat plate and back and $R_{\text{reflector}}$ the intensity reflection coefficient, for aluminium $\sqrt{0.84}$.

3.5. Equipment

Two transducers were investigated, both were of the unfocused single element type. The first was a commercially available transducer (V306, Panametrics, Waltham, MA, USA, PZT, 2.25 MHz centre frequency, diameter 12.7 mm), the other custom built (composite, 4.5 MHz centre frequency, diameter 1.5 mm). An arbitrary waveform generator (33250 A, Agilent, Loveland, Colorado) is used as a voltage source and connected directly to the transmitting transducer if necessary. The signal received by the transducer under scrutiny or hydrophone is attenuated by an attenuator (355D, Agilent, Santa Clara, CA, USA), amplified by a low noise amplifier (AU-3A-0110-BNC, Miteq, Hauppauge, NY, USA) and digitized by an oscilloscope (9400A, LeCroy, Geneva, Switzerland). Both the waveform generator and oscilloscope are connected to a computer through GPIB.

4. Results

4.1. Panametrics V306

The left graph of Fig. 3 shows the transmit transfer functions of a Panametrics V306 determined by the various methods, the right graph presents its receive transfer function.

The transfer functions determined by the different methods are similar and overlap. Except for the transfer spectra determined by the direct transmit experiment, which are significantly lower near 5 MHz. This is due to the presence

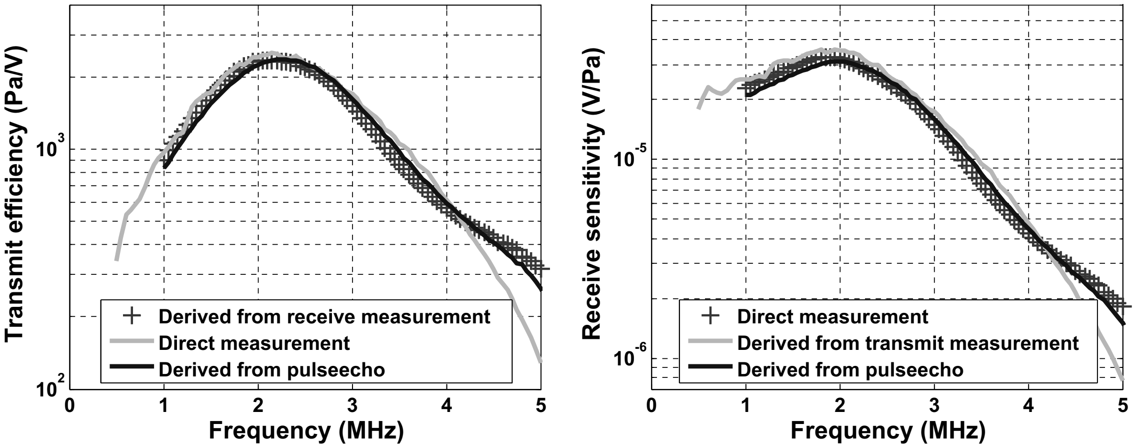

Fig. 3. The transmit and receive transfer function of a Panametrics V306 are shown in the left and right graphs, respectively.

of a low pass Butterworth filter with a cut-off point at 5 MHz in the measurement system. The accuracy is estimated at ±15%, which is close to the accuracy of the hydrophone used.

Notice the difference in shape between the transmit and receive transfer spectra, this is caused by the frequency dependency of the transducers impedance.

4.2. Custom made 1.5 mm transducer

The left graph of Fig. 4 shows the transmit transfer functions of the custom 1.5 mm transducer determined by the various methods, the right graph presents its receive transfer function.

The transfer functions determined by the different methods are similar. Below 2 MHz and above 7 MHz the SNR of the received signals was quite low. Between these frequencies the accuracy is estimated at ±15%, which is close to the accuracy of the hydrophone used.

Notice the difference in shape between the transmit and receive transfer spectra, this is caused by the frequency dependency of the transducers impedance.

5. Conclusion

The specific definitions of the transmit and receive transfer functions ensure that these transfer functions and the reciprocity theorem relating them are transducer characteristics and circuit independent.

All methods described are sufficiently accurate for absolute transfer function measurements, the particular choice of method is based on practical considerations. A reciprocal transducer can be completely characterized using a pulse-echo measurement and a vector impedance measurement, without the need for a hydrophone or calibrated transducer.

Because of these reasons, the proposed methods are particularly suited to select the optimal piezoelectric material (PZT, single crystal) for arrays used in reception only (3D scanning, superharmonic imaging) or to judge the performance of alternative transducer designs.

These methods are also important for selected experiments like single bubble behavior, where the complicated low pressure bubble response makes the precise absolute characterization of the measurement system mandatory.

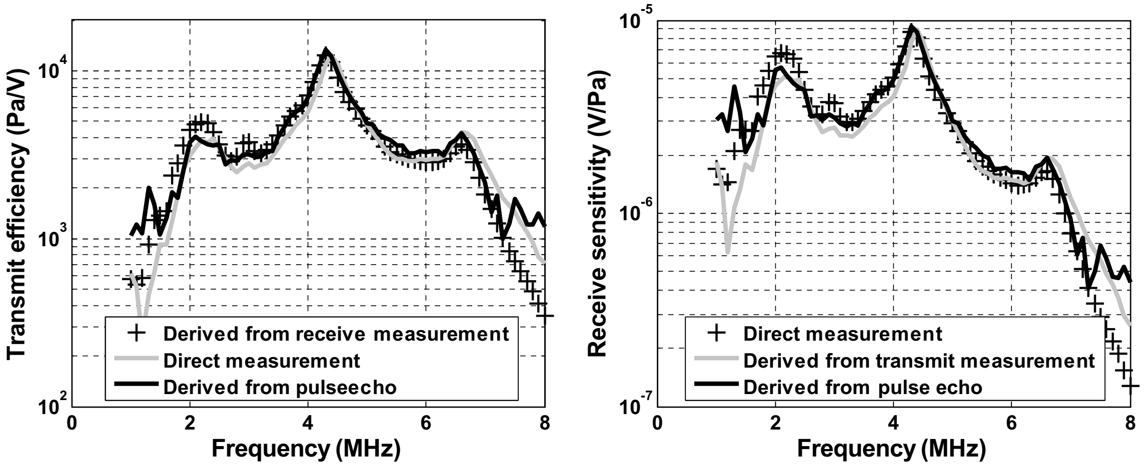

Fig. 4. The transmit and receive transfer function of the custom built 1.5 mm transducer are presented in the left and right graphs, respectively.

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