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Bandwidth Enhancement: Correcting Magnitude and Phase Distortion in Wideband Piezoelectric Transducer Systems

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1. Introduction

Acoustic ultrasonic measurements are widespread and commonly use transducers exhibiting resonant behaviour due to the piezoelectric nature of their active elements, being designed to give maximum sensitivity in the bandwidth of interest. We present a characterisation of such transducers that provides both magnitude and phase information describing the way in which the receiver responds to a surface displacement over its frequency range. Consequently, these devices work efficiently and linearly over only a very narrow band of their overall frequency range. In turn, this causes phase and magnitude distortion of linear signals. To correct for this distortion, we introduce a software technique, which considers only the input and the final output signals of the whole system which is therefore generally applicable to any acoustic system. By correcting for the distortion of the magnitude and phase responses, we have ensured the signal seen at the receiver replicates the desired signal. We demonstrate a bandwidth extension on the received signal from 60-130 kHz at -6dB to 40-200 kHz at -1dB in a test system. The linear chirp signal we used to demonstrate this method showed the received signal to be almost identical to the desired linear chirp. Such system characterisation will improve ultrasonic techniques when investigating material properties by maximising the accuracy of magnitude and phase estimations.

Piezoelectric transducers are used both as transmitters and receivers in many ultrasonic applications, including non-destructive testing, underwater sonar, radar and medical imaging (Blitz & Simpson, 1996; Urick, 1983; Greenleaf, 2001; Rihaczek, 1969). The transducer outputs are, however, significantly affected by the coupling between the transducer and the other components (e.g. the amplifier, and medium in which the energy propagates) (Fano, 1950) and the bandwidth of the system is also limited by the electro-acoustic performance of the transducers. A number of hardware techniques have been developed towards achieving a flat, broadband frequency response, using matching networks (Schmerr, 2006; Youla, 1964). The load is usually modeled as a resistor and capacitor (Reeder, 1972) or as a simple four-element circuit (Anderson, 1979). The problem with this approach is that, typically, the frequency responses of piezoelectric elements have resonant characteristics, which are difficult to accurately model using the passive component matching networks normally used. In most cases, improved results can be obtained if the network suggested by one of the techniques listed in (Schmerr, 2006; Youla, 1964; Reeder, 1972; Anderson, 1979) is used as a starting point for the hardware optimization approach, which in turn accounts for frequency dependent radiation in the equivalent circuits of the matching networks.

Recently, Doust (Doust, 2001) and Dix (Dou, 2000) introduced a hardware technique, in which they demonstrate improved overall phase linearity, efficiency and amplitude response of transfer functions, in an electro-acoustic system. Doust and Dix (Doust, 2001) sought to improve the accuracy of wave shape measurements and transducer response through compensating their system, comprising amplifiers, filters, and analog-to-digital converters. This was achieved by adding electronic circuits between the amplifier and transducer, and removing phase and amplitude distortion over a frequency spectrum, through a technique they refer to as equalisation. Distortion of the output signal in ultrasonic systems may be caused by many factors within any of the elements of the whole system, not only the transducer elements alone. Often the physical value (e.g. pressure) and the distorted waveform resulting from the conversion processes are repetitive with respect to time, for example current waveforms in alternating current power systems. At any frequency, the transducer, amplifier, filter, or A/D converter can distort the signals introducing errors in the amplitude, phase or both, which can in turn introduce distortion in reconstructed waveforms. The hardware equalisation of Doust (Dou, 2000) achieves this by taking into account all the subsystems and equalising each subsystem in turn.

This hardware method requires a knowledge of the transfer functions of all the components in the system, which maybe difficult to determine (e.g. transfer function of the medium). On the other hand, the software approach, described below, achieves the same but in a single operation, without knowledge of the transfer functions. Consequently, it has the potential to compensate amplitude and phase distortions in whole systems. In essence, we consider the overall system as a 'black-box' and attempt to correct the output by compensating the input on the basis of the system phase and magnitude frequency-responses.

2. Methods

This chapter describes a software method and associated procedures for characterising a system in terms of its magnitude and phase response with respect to frequency; this is then applied experimentally to improve the effective bandwidth of the whole system. The need for transducer characterisation is highlighted through the realisation that the performance of a system may not be known and that assumptions are often made regarding the signal being injected into the medium. Our strategy is to ensure signals with precisely known amplitude and phase are used as inputs to subsequent signal processing methods. Tone burst signals, used for the sensor characterisation, were produced using a piezoelectric transducer driven by an Agilent 33120A function generator. To demonstrate this methodology as a means of improving bandwidth, a series of measurements were performed using ultrasound transducers developed by Alba Ultrasound Ltd. These underwater transducers were designed to have a wide bandwidth with a centre frequency between 100-130 kHz, operating effectively as both transmitters and receivers of ultrasound with 92 mm size diameter and a beam angle of 10° on the primary lobe. The transmitter was driven directly with a 10 V peak-to-peak, 10-cycle tone burst made over a range of frequencies from 40 to 200 kHz sampled at 10MHz and the receiver was connected directly to the oscilloscope. A total of 10000 points were recorded for each waveform at each measurement frequency. A transmitter-receiver separation of approximately 0.5 m was selected as shown in figure 1. We decided to take 2500 samples for each tone-burst to ensure 4 kHz resolution. With this window length and frequency resolution, two sets of 41 signals each starting at 40 kHz, and rising in steps of 4 kHz, to 200 kHz were generated. Using frequencies at this step interval enables the frequency

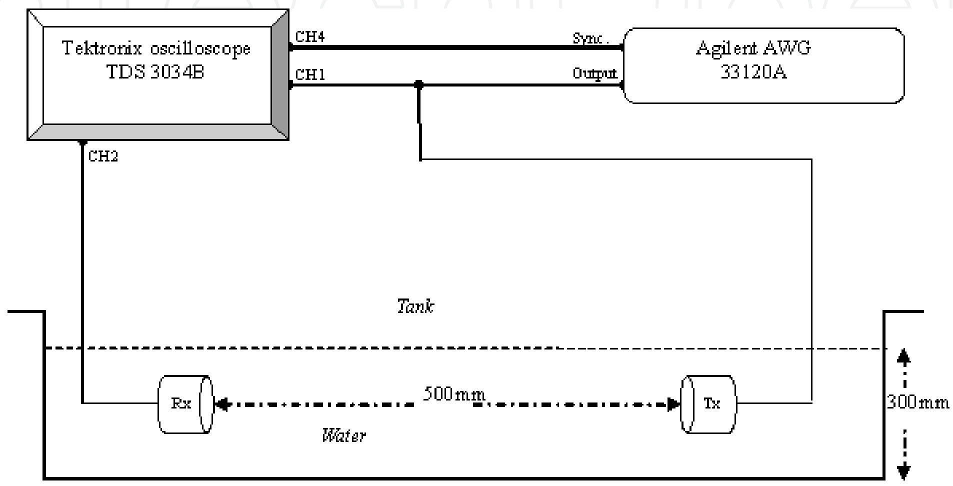
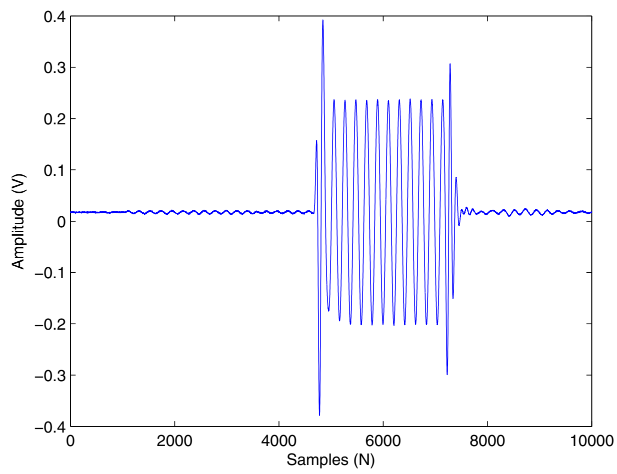


Fig. 1. Schematic diagram of experimental setup.

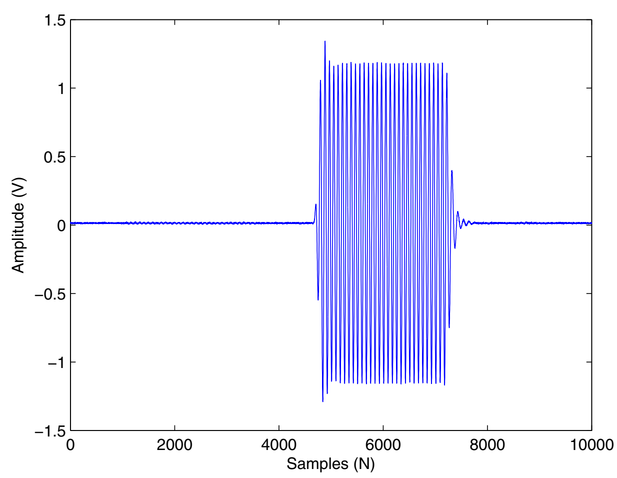
to be determined exactly on a DFT frequency bin and hence, give an accurate measure and minimise spectrum leakage of the response at that frequency. Furthermore, the length of signals chosen was short enough to avoid interference from multi-path reflections from tank walls. Both sine and cosine signals were generated at each of the corresponding frequencies. These were designated $r0.txt$ and $i0.txt$ for the real (cosine) and imaginary (sine) signals for the first frequency set0, for example. The sets were sequentially numbered from 0 to 40. Examples of the received signals obtained at 48 kHz and the 120 kHz are shown in figure 2a and 2b, respectively. In order to provide a more accurate estimation of the spectrum, we excluded samples affected by the "switch on" and "switch off" of the transducer (see figure 2), taking 700 samples either side of the centre of this 2500 samples long received 'tone-burst' signal for our analyses. This provides 1400 samples about the centre of the 'tone burst' time window avoiding the effects of ringing and reflections. Consequently, we designed two sets of 41 test signals (0...40) each, real and imaginary, in steps of 4 kHz starting at 40 kHz and ending at 200 kHz. Each test signal was transmitted as a continuous sine and cosine wave 'tone-burst' having a $250\mu s$ duration. The discrete Fourier Transform (DFT) of the centre portion (1400 samples) of each received signal was performed.

3. Transducer characterisation and bandwidth enhancement

Having obtained this set of 41 values (via DFT of the sine and cosine sets) over the frequency range, we calculated the response (41 frequency bins) of the system in terms of magnitude and phase with respect to the frequency, as shown in figures 3a and 3b, respectively. We can see in figure 3a, there is a 35 dB variation in magnitude about the centre frequency of 100 kHz. Similarly, the phase in figure 3b is changing rapidly in the centre band of frequencies.



(a) Received signals in the lower transducer sensitivity (48 kHz).



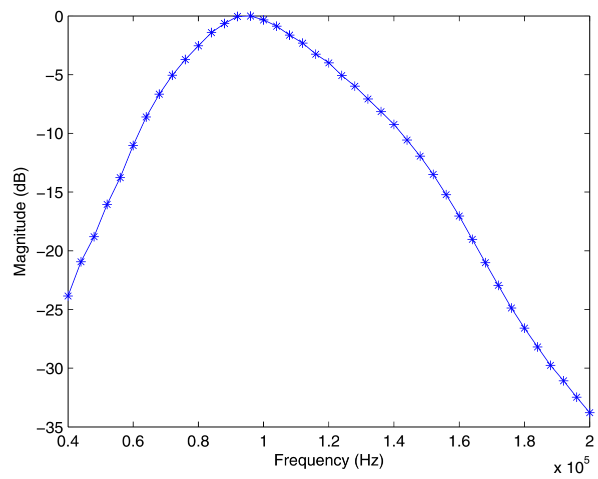
(b) Received signals in the higher transducer sensitivity (120 kHz).

Fig. 2. Examples of received signals.

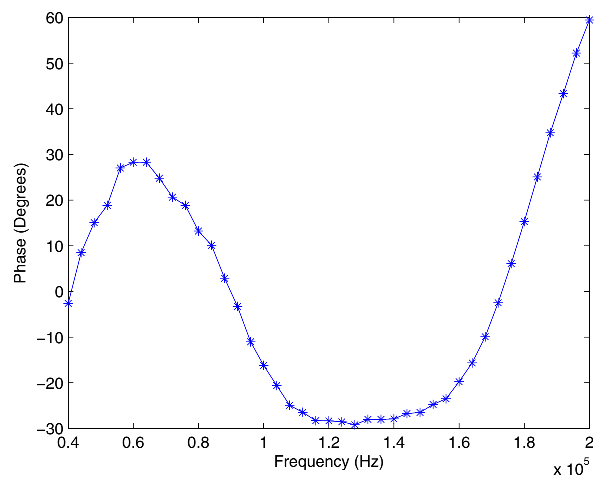
Using the magnitude and phase responses, described above, the signals were compensated in the time domain in a way similar to inverse filtering, as described below. As a check, the received signals were then used to obtain new sets of magnitude and phase responses as shown in figures 4a and 4b, respectively. Variations in the magnitude and phase responses can be seen to be drastically reduced, following our compensation based on characterising the whole system, magnitude and phase variations being reduced from 35 to 0.6 dB and from 90 to 6 degrees, respectively, resulting in an improvement in the effective bandwidth from 60-130 kHz at -6 dB to 40-200 kHz at -1 dB.

4. Linear chirp compensation

To test the compensated system performance, a linear chirp signal was used. As the characterisation used 41 discrete points in the frequency band, it was necessary to interpolate



(a) Plot of the 41 magnitude responses related to the 41 transmitted frequencies (35dB variation).



(b) Plot of the 41 phase responses related to the 41 transmitted frequencies (90 degree variation).

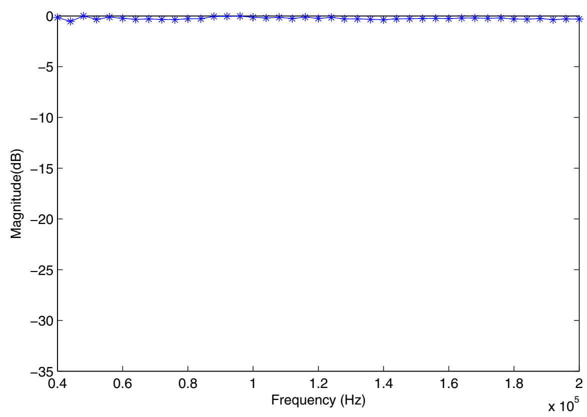
Fig. 3. Magnitude and phase responses.

the magnitude and phase responses between these discrete points at all the desired frequencies; we used the *Matlab* 'interp1' function with 'cubic' interpolation. For the purposes of the calibration, 2500 points were used to generate the chirp signal at a sampling frequency of 10 MHz (as described above). The 41 points of the magnitude and phase responses were interpolated to 2500 values as follows:

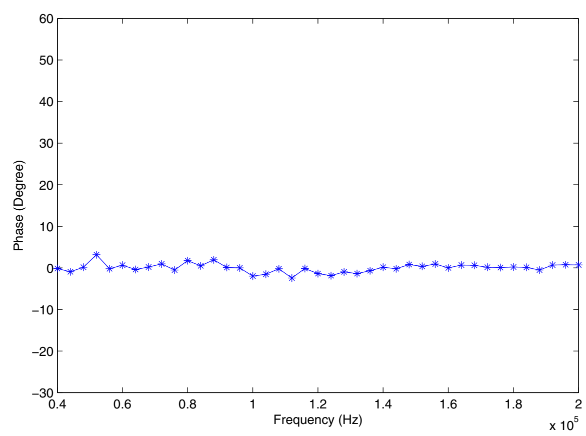
$$newA = interp1(t, TransferHR(2,:)', new_t, 'cubic'). \tag{1}$$

where *newA* is the amplitude at the required new points, new_t is the time of each of the 2500 new samples points, t is the time at the original 41 points and *TransferHR(2,:)* contains the original '41 value' magnitude response. A similar calculation was performed for phase using

$$newP = interp1(t, TransferHR(3,:)', new_t, 'cubic'). \tag{2}$$



(a) Plot of the 41 magnitude responses related to the compensated transmitted 41 frequencies (0.6 dB variation).



(b) Plot of the 41 phase responses related to the compensated transmitted 41 frequencies (6 degrees variation).

Fig. 4. Magnitude and phase responses after compensation.

where *newP* was an array of 2500 phase values, and *TransferHR(3,:)* contains the original ’41values’ phase response. Consequently, the compensation for both magnitude and phase was achieved in a single operation in which, the amplitude of the signal will be multiplied by the factor "$max(newA)/newA$" and the phase by "$-newP$". To validate the method, we selected a broadband chirp signal having a frequency range comparable to the transducer response. A Gaussian window was applied to the transmitted signal to minimise the unwanted ’turn on’, ’turn off’ signals, seen originally in figure 2. These signals are shown in figures 5a and 5b after applying a digital low pass Butterworth filter (0-400 kHz) to eliminate undesirable high frequencies. Our results show a significant difference in the signal excitation (figure 5b) to the one transmitted before (figure 5a). The signal in figure 5b was compensated in relation to the magnitude and phase response ’transferHR’ developed as a result of the software characterisation. Figure 6a shows the signal received when the original Gaussian chirp (figure 5a) is transmitted. When the compensated signal was applied to the transmitter (figure 5b), a Gaussian chirp signal was received (figure 6b) similar to the

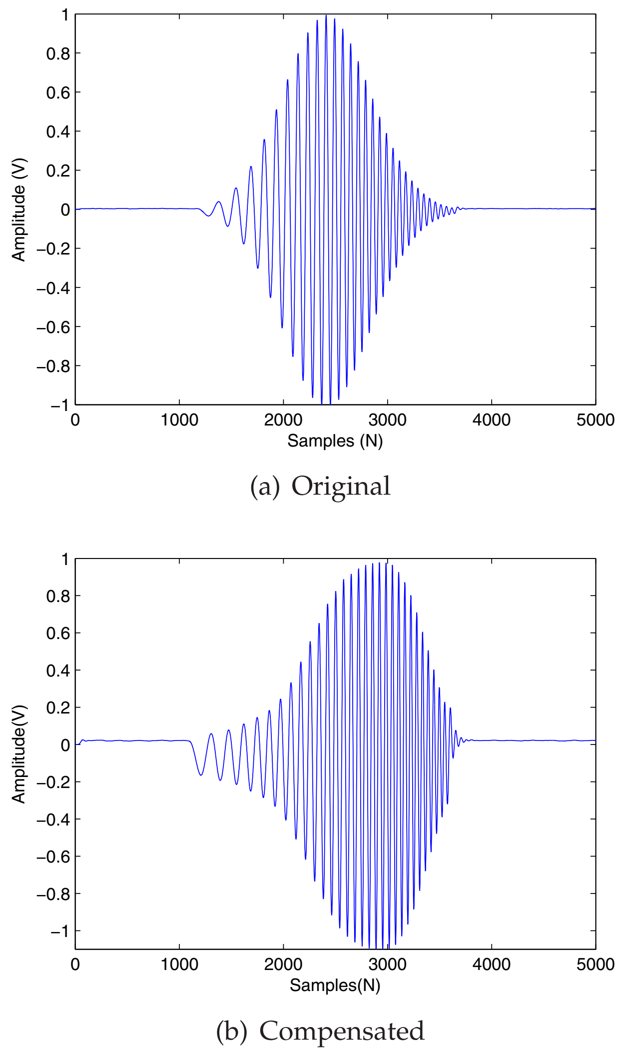
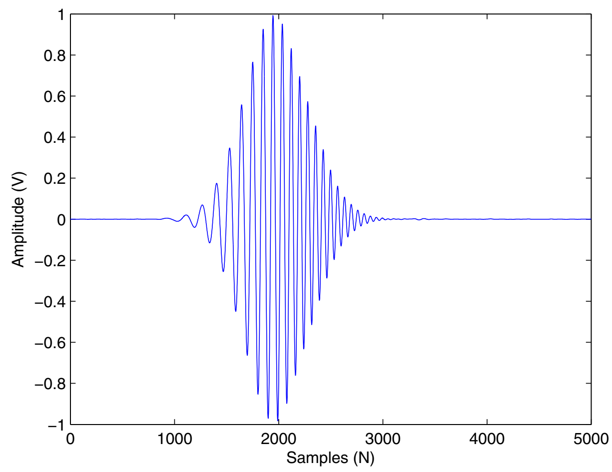


Fig. 5. Transmitted gaussian chirps signals [40-200 kHz].

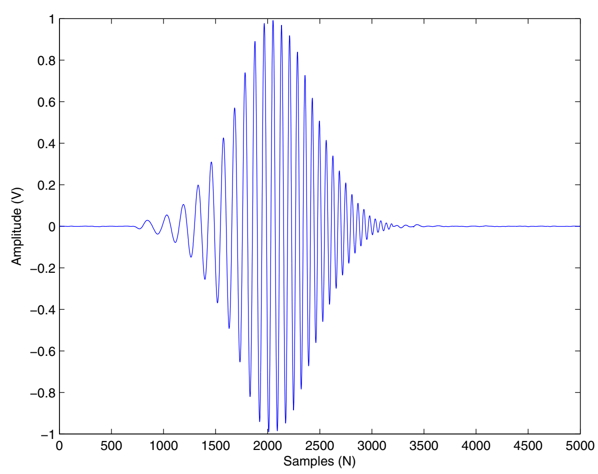
original 'Gaussian' chirp (figure 5a). Thus, the compensation technique can be seen to be effective. An amplitude comparison was undertaken using the envelope of the signals. The envelopes were determined by transforming a time signal into an analytic signal using the Hilbert transform and determining the absolute value of the analytic signal. In figure 7a, the solid curve represents the Hilbert Transform (HT) of the original transmitted signal and the dashed curve represents the HT of the corresponding received signal. Figure 7b shows the HT of the transmitted original signal (solid curve) and the HT of the signal received, following compensated transmission (dashed curve), showing the signals to be almost identical.

5. Results and discussion

In this chapter, we demonstrate a novel software method to improve whole ultrasonic transmitting-receiving systems. Distorting the input signal, on the basis of characterising the magnitude and phase response of the whole system, enabled us to acquire desired signals at the output with little distortion, using piezoelectric transducers in a broadband transmitting and receiving system. Using a linear chirp as a test signal, we validated our method over a



(a) Original

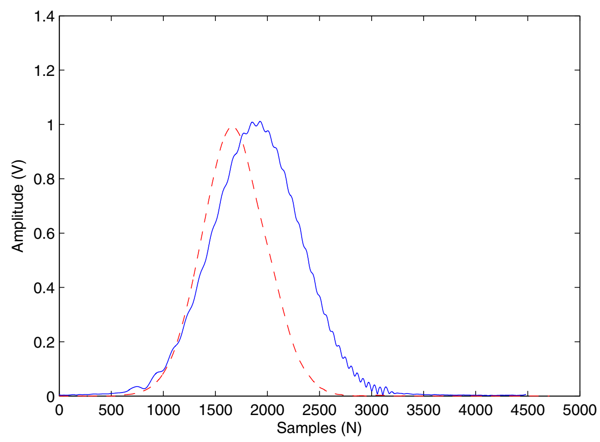


(b) Compensated

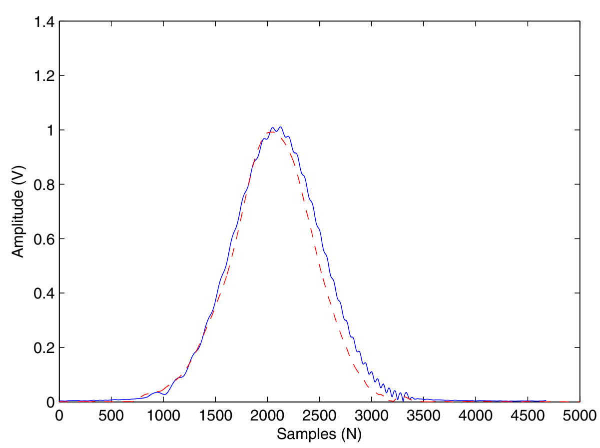
Fig. 6. Received gaussian chirps signals [40-200 kHz].

range of frequencies. The results showed close resemblance between the desired and received signals. Our characterisation approach has enabled the effective bandwidth of the system, as a whole, to be significantly improved from 60-130 kHz at -6dB to 40-200 kHz at -1dB. Additionally, such system characterisation is necessary when using ultrasonic techniques to investigate material properties; it is necessary to control signal properties, otherwise the signals will not be sensitive enough to the analysis necessary to identify changes in material properties in terms of changes in their magnitude and phase, for example. Such signals are intended for use in experiments leading to techniques for improved imaging, physical properties characterisation of materials and investigation of material heterogeneity.

The presented technique characterises the effect of the transmission and reception process of acoustic transducers. This enables further measurements to be corrected to remove the effects of the transducers and improve analysis of the wave propagation characteristics.



(a) The Hilbert Transforms of the original transmitted signal (solid curve) and original received signal (dashed curve).



(b) The Hilbert Tranform of the original transmitted signal (solid curve) and the signal received following compensated transmission (dashed curve).

Fig. 7. Compensating the transmitted signal results in the receive signal being almost identical to that originally transmitted (i.e. the desired signal).

6. Acknowledgments

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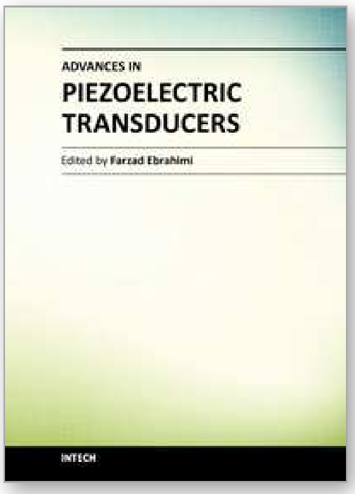

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