# An approach for correcting magnitude and phase distortion in wideband piezoelectric transducer systems.

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**Abstract**—Acoustic ultrasonic measurements are widespread and commonly performed using sensitive piezoelectric sensors. An accurate transducer system response to investigate pressure fluctuations in water and their subsequent detection remains a challenge. Typically, these sensors exploit the resonant behaviour of the piezoelectric active element, being designed to give maximum sensitivity in the bandwidth of interest. Calibration of such transducers can provide both magnitude and phase information describing the way in which the sensor responds to a surface displacement over its frequency range. Such resonant sensors are widely used for ultrasonic applications. The resonant nature of the sensors leads to the use of narrowband signals with central frequencies close to the resonant frequency of the piezoelectric element. Consequently, such devices work efficiently and linearly over only a narrow band of their overall frequency range. This causes phase and magnitude distortion of any linear broadband signal being transmitted through such a transmitter-receiver acoustic system. In the present work, we describe a software calibration technique to correct for distortion in a wideband piezoelectric transducer system. We consider only the input and the final output signals of the whole system. Compensating for the distortion of the magnitude and phase responses, we ensured the signal seen at the receiver represents a good replica of the desired signal. A Gaussian, linear, chirp signal was used to demonstrate our approach. This method may be applied to correct system distortion in a wide variety of ultrasonic applications.

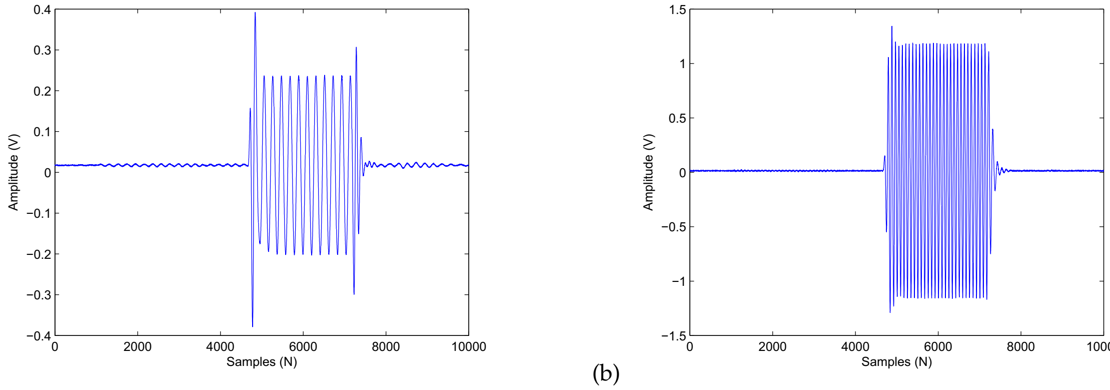
**Index Terms**—Acoustic; Ultrasonic; Transducer; Calibration; Chirp Signal.

## 1 Introduction

Piezoelectric transducers are used both as transmitters and sensors in many ultrasonic applications such as non-destructive testing, underwater sonar, and medical imaging [1-4]. However, the transducer outputs are significantly affected by the coupling between the transducer and the other components (e.g. the amplifier, and medium in which the energy propagates) [5]. This means that coupling must be carefully considered if reliable acoustic signals are to be generated and used for system calibration. The overall accuracy measurement and bandwidth of the system is therefore limited by the performance of the transducers. A number of hardware techniques have been developed to design flat broadband frequency response matching networks [6-8] for acoustic transducers. The load is usually modelled as a resistor and capacitor [9] or as a simple four-element circuit [10]. The problem with this approach is that, typically, the frequency responses of piezoelectric elements have resonant characteristics, which are difficult to accurately mimic using fixed component networks. In most cases, improved results can be obtained if the network suggested by one of the techniques listed in refs [6-10] is used as a starting point for an optimization routine, which accounts for frequency dependent radiation resistance and reactance. Recently, Doust and Dix [11] introduced a hardware calibration technique, in which he demonstrated improved overall phase linearity, efficiency and amplitude response of transfer functions, in an electro-acoustic system. The calibration method of Doust and Dix seeks to improve the accuracy of wave shape measurements and transducer response. Specifically, it is a method and apparatus, which calibrates a system, comprising: amplifiers, filters, and analog-to-digital converters. This is achieved by adding electronic equalisation devices between amplifier and transducer, removing phase and amplitude errors over a frequency spectrum. They called this technique equalisation. Distortion of the output signal in ultrasonic systems may be caused by many factors within the elements of the whole system, not only the transducer elements alone. It is often the case that the physical value (e.g. pressure) and the distorted waveform resulting from the conversion processes are repetitive with respect to time, current waveforms in alternating current power systems, for example. In these cases the original waveform of the physical value and the associated distorted waveform resulting from the conversion process can be decomposed into Fourier series of pure sine and cosine waves, with each wave having a unique frequency, amplitude and phase. At any frequency the transducer, amplifier, filter, or A/D converter can distort the signals introducing errors in the amplitude, or phase or both, which can in turn introduce distortion in reconstructed waveforms. These repetitive errors are frequency dependent; consequently, the hardware method and apparatus for digital calibration are incapable of correcting for them. A method and apparatus are needed for calibrating systems that convert time-varying physical values having repetitive waveforms, to accurate digital values. Doust's hardware calibration achieves this by taking into account all the subsystems and calibrating each subsystem in turn [12]. The software calibration method described below has the potential to remove amplitude and phase errors in the transducers, amplifiers, and analog-to-digital converters, by considering these devices as one system. Such a software calibration method has the benefit of simplicity and excludes a need to know the transfer function of each subsystem component (e.g. filter, amplifier, transducer). In essence, we consider the overall system as a 'black-box' and attempt to correct the output by compensating the input in terms of its phase and magnitude frequency responses.

## 2 Methods

This paper describes a software calibration method and associated procedures plus an experimental example, calibrating a system for its magnitude and phase response with respect to frequency; the experimental work was performed at the British Geological Survey Laboratories, Keyworth, UK. The need for calibration is highlighted when one realises the actual performance of a system may not be known and assumptions are being made as to the signal actually being injected into the medium. A prime purpose of this experiment is to show signals having precisely known amplitude and phase can be injected. Tone burst signals, used for the sensor calibration, were produced using a piezoelectric transducer driven by an Agilent 33120A function generator. The function generator produced tone-burst signals, which were digitised using a Tektronix TDS 3034B oscilloscope. To demonstrate this methodology of calibration, 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. They were designed to operate effectively as both transmitters and receivers of ultrasound with a beam width of around 10 degrees at the device centre frequency. The maximum electrical conductance of the transducer in water is 1.14 ms at 92.6 kHz and the -3dB bandwidth is 99 kHz (72 kHz to 171 kHz). The mechanical quality factor (Q) is 1.23 (transmitter serial no 001, receiver serial no 003). The transmitter was driven directly with a 10 V peak-to-peak, 10-cycle tone burst from the function generator (see above). The receiver was connected directly into the oscilloscope. Both transducers were mounted in a small water tank at a separation of 0.5m. Signals were digitised using a Tektronix TDS 3034B oscilloscope. Measurements were made over a range of frequencies from 40 to 200 kHz. A total




(a) (b)

**Fig1.** Example of received signals: (a) 48kHz. (b) 120kHz

of 104 points were recorded for each waveform at each measurement frequency. This tone-burst approach is suited to ultrasonic transducers, which are specifically designed to be used at or close to their resonant frequency, allowing a good representation of the transducer's performance at discrete frequencies across its bandwidth. The transmitter-receiver separation of 0.5m was selected to give a two-way travel time of 667 $\mu s$, where the sound velocity is $1500 m/s$ in the surrounding medium (i.e. water). The sampling frequency was 10 MHz. This propagation time and sampling frequency, gave a signal length $(10^7 \times 667 \times 10^{-6}) = 6670$ samples, or in terms of frequency resolution (fs/N) 1500 Hz. We decided to take just 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. The 2500 samples used gave 10 cycles for the lowest frequency tone-burst (40 kHz), which is enough to compute the Discrete Fourier Transform (DFT), for example. Using frequencies at this step interval enables the frequency 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, with the length of signals chosen we also avoided interference from reflections from the tank walls. Both sine and cosine signals were generated at each of the calibration 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. An example of the received signals for the 48 kHz and the 120 kHz tone-burst signals is shown in figure1.

In order to provide a good estimation of the spectrum, we excluded samples affected by the switch on and switch off, of the resonant transducer (see figure 1), 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. In fact, the only frequency computed and used for the calibration was the actual frequency of the test signal being analysed. Magnitude and phase responses were computed for all the 41 signals.

## 3 Calibration

Having obtained this set of 41-calibration 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 figure 3. We can see from the figure 3, there is a considerable variation at low and high frequencies in magnitude. Similarly, the phase in figure 6 is changing rapidly in the centre band of frequencies. Using these magnitude and phase responses, the signals were compensated then re-sent, by altering the amplitude and phase according to the 'tone-burst' response functions in a such way as to create a flat response. The received signals were then used to obtain new sets of magnitude and phase responses as shown in figure 4. Variations in the

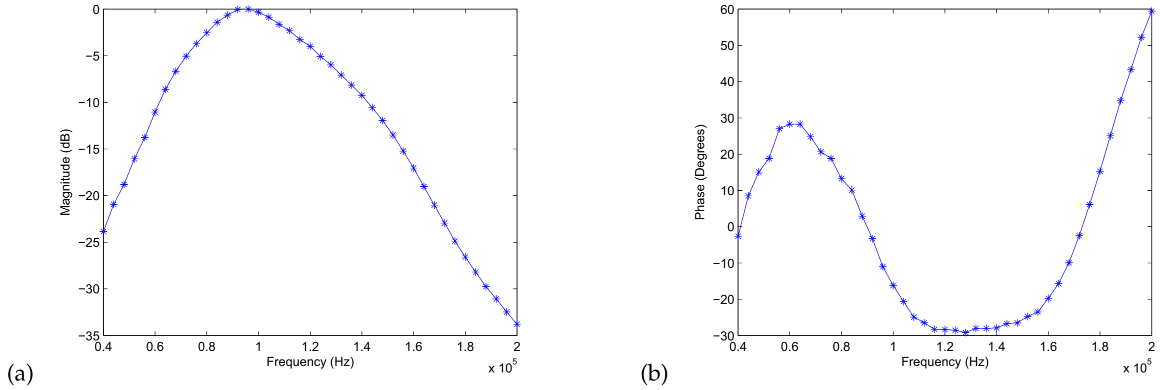



**Fig2.** Magnitude and phase responses: (a) Magnitude variation(35 dB). (b) Phase variation (90 degree)

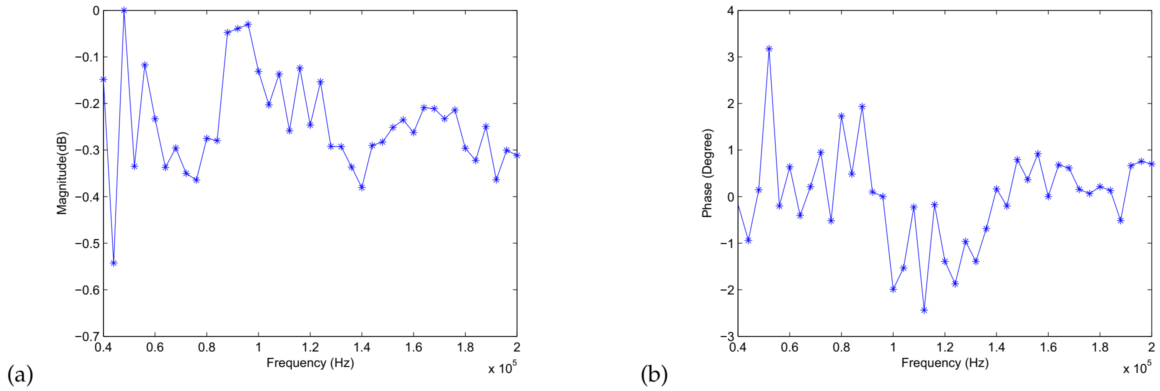



**Fig3.** Magnitude and phase responses after compensation: (a) 0.6 dB variation. (b) 6 degree variation

magnitude and phase responses can be seen to be drastically reduced, following our compensation (based on calibrating the whole system). The phase compensation is within $\pm3$ degrees over the entire frequency band, a considerable improvement over the original 90-degrees variation. The magnitude was flat to within 1dB, again a considerably less than the original variation of 35dB ( i.e. a 30 times reduction in the variation of both magnitude (dB) and phase (degrees) responses).

## 4 Linear chirp compensation

In order to test the method, we applied it to compensate a chirp signal. Since we use responses at 41 discrete points in the frequency band, it was necessary to interpolate between discrete points to calculate the response at all the desired frequencies in order to compensate the chirp signal. 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 using

$$newA = interp1(t, THR(2,:)', newt,' cubic') \quad (1)$$

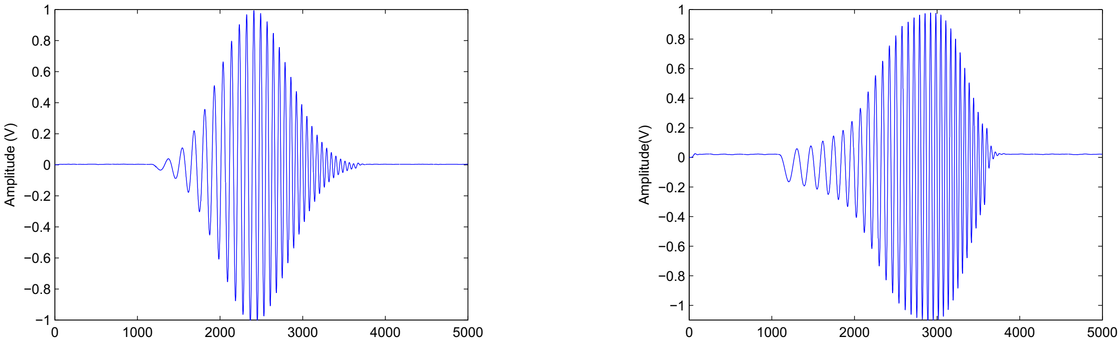
where newA is the amplitude at the required new points, newt is the time of each of the 2500 new samples points, t is the time at the original 41 points and THR(2,:) contains the original '41 value' magnitude response. A similar calculation was performed for phase using

$$newP = interp1(t, THR(3,:)', newt,' cubic') \quad (2)$$

where newP was an array of 2500 phase compensation values, and THR(3,:) contains the original '41values' phase response. Consequently, the compensation for both magnitude and phase could be achieved in one operation.

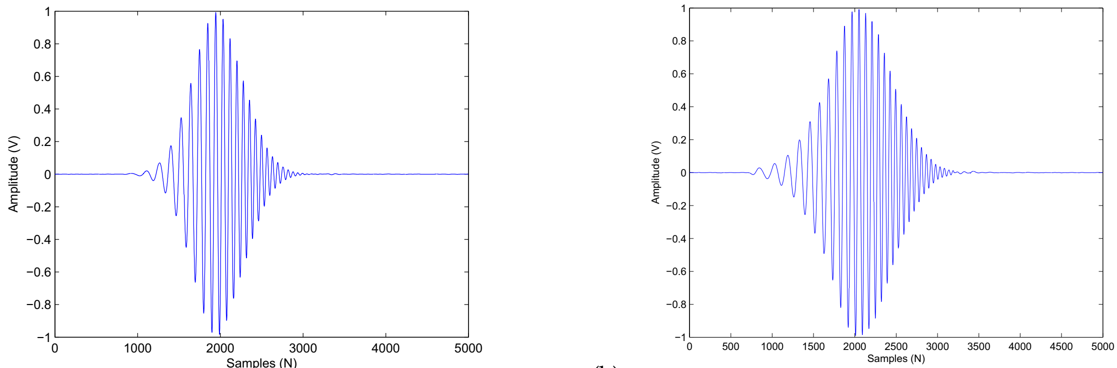
## 5 Results and discussion

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 in order to minimise unwanted 'turn on', 'turn off' signals seen



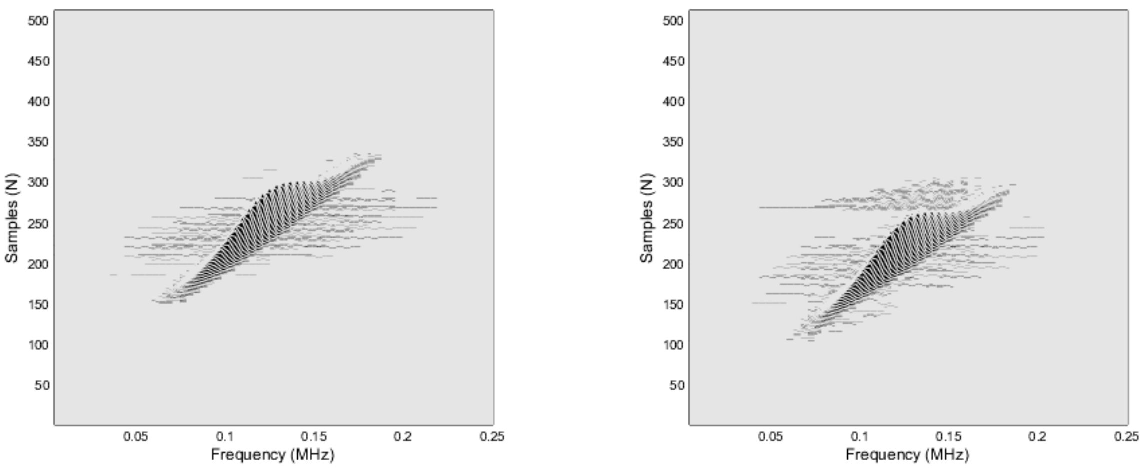

(a) (b)

**Fig4.** Linear Gaussian chirp: (a) Original (Transmitted). (b) Compensated (transmitted)




(a) (b)

**Fig5.** Linear Gaussian chirp: (a) Original (received). (b) Compensated (received)




(a) (b)

**Fig6.** Smoothed Wigner-Ville: (a) the transmitted original chirp. (b) the received compensated chirp

originally (figure 1). The signals are shown in figure 5 after applying a digital low pass Butterworth filter (0-400 kHz) to eliminate undesirable high frequencies. We can see a significantly different signal (figure 5b) to that propagated originally (figure 4b). The signal in figure 5b is compensated in relation to the magnitude and phase response 'transferHR' developed as part of the software calibration. Figure 5a shows the signal received when the original Gaussian chirp (figure 4a) is transmitted. When the compensated signal was applied to the transmitter (figure 4b), a Gaussian chirp signal was received (figure 5b) similar to the original 'Gaussian' chirp (figure 4a). Thus, the compensation technique can be seen to be effective. A time-frequency analysis was undertaken using the original transmitted and compensated received chirp signal (after sub sampling the signals to 1 MHz) to show their resemblance. The results in figure 6a and 6b, using the smoothed Wigner-Ville distribution under the TFSA Matlab toolbox developed by Boashash [12], show the signals to be almost identical.

## 6 Conclusion

In this paper, we demonstrate a software method to calibrate whole ultrasonic transmitting-receiving systems for magnitude and particularly phase distortion. Distorting the input signal on the basis of the magnitude and phase response of the whole system enabled us to acquire the desired signal 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 this method over a range of frequencies, as the results showed close resemblance between the desired and received signals. Such system calibration is necessary when using ultrasonic techniques to characterise materials. For example, to control signal properties, otherwise the signals may not be sensitive to the analysis necessary to identify materials properties in terms of changes in their magnitude and phase. Such 'calibrated' signals are intended for use in experiments investigating techniques for improved imaging, physical properties characterisation of materials and investigation of material heterogeneity.

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