ABSOLUTE ULTRASONIC MEASUREMENTS WITH PIEZOELECTRIC TRANSDUCERS

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ABSTRACT

The absolute calibration of a piezoelectric transducer refers to the determination of the relationship between the electrical and acoustical quantities for a transducer coupled to a solid. It is shown how a well-characterized ultrasonic system, consisting of source, structure and receiver can be used to make such measurements for transducers operating as sources or receivers. Results are given, showing the effects of coupling between transducer and solid and the electrical characteristics of the associated source and receiver electronics.

This poster paper describes the principles and procedures for making absolute ultrasonic measurements with a piezoelectric transducer coupled to a solid. Publication of these results will be in the *1979 Ultrasonics Symposium Proceedings* [1].

As described in a recent review article [2], the complete characterization of an ultrasonic transducer acting as source or receiver entails two parts. One part deals with the tranduction process in which the relationship between electrical and mechanical quantities is established. The second deals with the characterization of the radiation field of the transducer. This paper concerns itself with measurements which characterize the transduction process of a piezoelectric transducer coupled to a solid.

INTRODUCTION

As elaborated in the review article by Sachse and Hsu [2], several assumptions need to be made in order to permit a ready characterization of the transduction process. As shown in Figure 1, a transducer operating as a source may involve processes which are not well understood or difficult to describe precisely. The excitation voltage and current imposed on a transducer result in a complicated distribution of time-dependent surface tractions and displacements (or velocities) each with longitudinal and shear components, acting over the transducer area on the specimen. Only when one makes the simplifying assumptions of mode uncoupling, field variable independency and linear system response does one find a simple matrix relationship between the electrical excitation parameters and the resulting mechanical excitation. Then, when restricted to a fixed specimen and electronics can a relationship between electrical excitation and produced mechanical force be written in terms of a linear transfer function equation in either the time- or frequency-domains,

$$F_0(t) = T_0(t) * V_0(t) \quad (1a)$$

or

$$F_0(\omega) = T_0(\omega) \cdot V_0(\omega) \quad (1b)$$

With similar assumptions, an analogous description is obtained for a transducer operating as a receiver,

$$V(t) = T(t) * U(t) \quad (2a)$$

or

$$V(\omega) = T(\omega) \cdot U(\omega) \quad (2b)$$

The above equations show that once the transfer function of a transducer is determined, the relationship between electrical and acoustical quantities across the transducer is established.

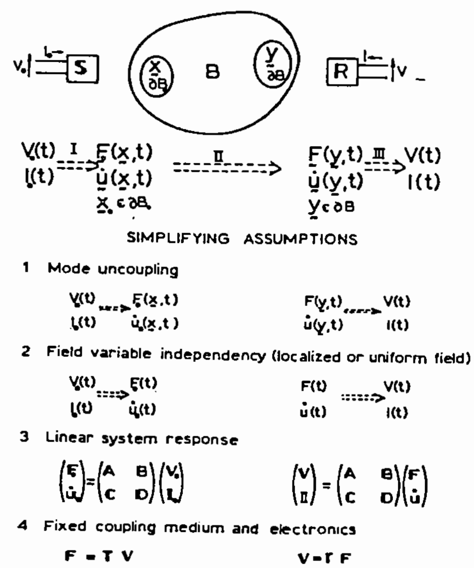
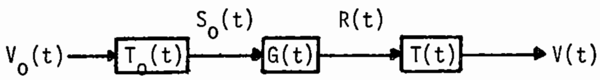


Figure 1 - Simplifying assumptions of the transduction process. (from Ref. 2)

Recent experiments in which the deterministic aspects of acoustic emission have been studied have utilized a well-characterized ultrasonic system in which the characteristics of the source, structure and receiver can be independently measured or determined [3-5]. Here, the signals emitted by a known source (either electrical or mechanical) are propagated in a structure for which the impulse response is known. The signals are detected with a sensor whose transduction characteristics are also known. Such a system is over-determined, and thus it allows substitution of an unknown source or receiving transducer into the system and, provided that the system is linear, the time- or frequency-characteristics of the transducer can be ascertained by linear signal deconvolution procedures.

METHOD

An ultrasonic system in which the various components comprising it are isolated is shown schematically in block form in Figure 2. When the



$$V(t) = \underbrace{\{(V_0(t) * T_0(t))}_{S_0(t)} * G(t)\} * T(t)$$

Figure 2 - A linear ultrasonic system.

excitation voltage, $V_0(t)$, is applied to the transducer whose transfer function is $T_0(t)$, the excitation force, $S_0(t)$, is produced in the specimen.

For cases in which the assumptions of mode uncoupling and field variable independency are valid, the impulse response of the structure G(t), which depends on the type of source and receiving transducer, can readily be computed for any arbitrary locations of the transducers. The signal, R(t), at any point is converted to a voltage, V(t), by the receiving transducer whose transfer function is T(t). Thus, for a linear, ultrasonic system, the received signal can be written as a convolution of the characteristics of each of the elements comprising the system, that is,

$$V(t) = V_0(t) * T_0(t) * G(t) * T(t) \qquad (3)$$

Depending on the calibration to be done, the source used in the measurement may either be electrical (i.e. $V_0(t)$) or mechanical (i.e. $S_0(t)$) with the latter being used in place of the electrically produced excitation: $V_0(t) * T_0(t)$. In either case, a fast risetime excitation pulse works best. The propagating medium used, is a structure for which the theoretical impulse response is known. In the present experiments, a thick flat plate is used for which the impulse response has been computed by Pao, et al. [6]. An electrostatic, capacitive transducer or a special piezoelectric transducer was used as a displacement sensor having transfer characteristics $T(t) = A\,\delta(t)$ for some time interval.

Shown in Figure 3 is a comparison between the computed vertical displacements and the measured voltage of such a transducer when the excitation was a vertical step unloading directly under the receiver on the opposite side of the plate (i.e. plate epicenter). The agreement indicates how accurately the modelled source structure and receiver corresponds to the actual system.

MEASUREMENTS

Ultrasonic Force Function Determination - In order to determine the temporal characteristics of the force generated in a specimen by a source transducer, the signal V(t) detected by a receiving transducer is measured and the transducer-generated force function is determined from

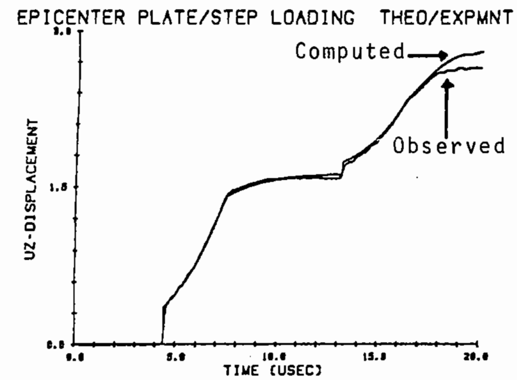


Figure 3 - Epicentral displacement: step unloading. Computed, observed.

$$S_0(t) = [G(t)]^{-1} * V(t) \qquad (4)$$

To illustrate such a determination, ultrasonic signals were produced by a broadband longitudinal wave transducer which was shock excited with various electrical pulses produced by a pulser for which the output impedance could be adjusted between 5 and 250 Ω. The excitation voltage pulses ranged from -225 Volts/50 nsec to -325 Volts/100 nsec. The detected displacement signals were deconvolved according to Eq. (4) and the excitation forces, $S_0(t)$ determined. The results are shown below in Fig. 4.

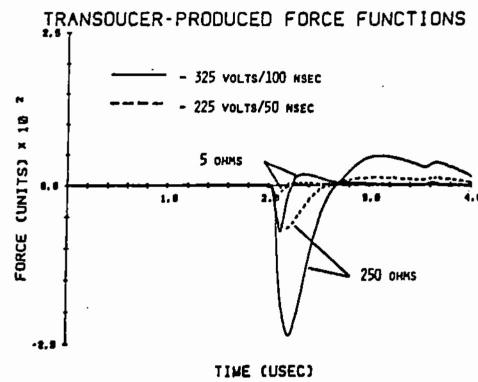
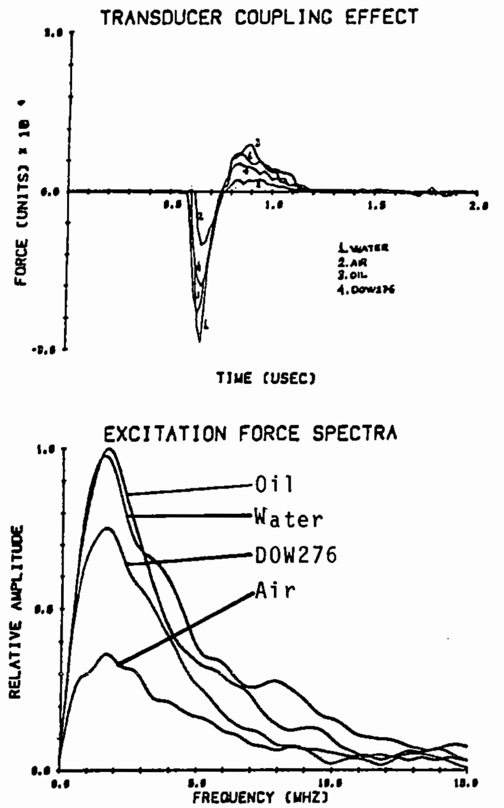


Figure 4 - Transducer-generated forces in a specimen of glass. Variable excitation voltage, damping.

To investigate the influence of transducer coupling on the generated ultrasonic excitation pulse, various couplants were used to attach a broadband longitunial wave transducer to a glass plate. The couplants investigated were light-weight machine oil, water, DOW 276-V9, and air. The time-characteristics of the generated excitation forces produced in the glass specimen were determined again according to Eq. (4). These are shown in Figure 5(a). The force-time functions were transformed into the frequency domain to further investigate the transmission characteristics of these couplants. As shown in Fig. 5(b), the frequency characteristics of the generated ultrasonic forces appear to be quite similar for these couplant materials in this frequency range. These measurements suggest the possibility for systematically investigating the characteristics of various transducer



Figures 5(a) and 5(b) - Transducer Coupling Effect.

couplant materials.

Source Transducer Transfer Function - As indicated previously, the transduction characteristics of a transducer coupled to a particular specimen and ultrasonic signal source can be specified in terms of its transfer function, $T_0(t)$. The transducer-produced ultrasonic force is given by

$$S_0(t) = V_0(t) * T_0(t) \qquad (5)$$

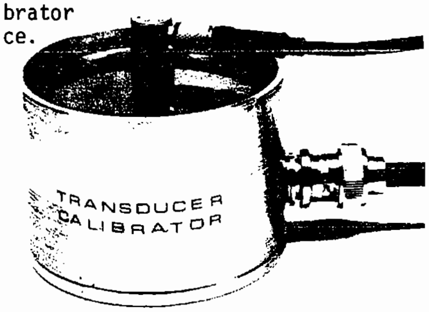
This force function can also be determined by using Eq. (4) to deconvolve the displacement signal detected at some point on the specimen. Thus, Eq. (4) and (5) can be combined to allow determination of the source transducer's transfer function, $T_0(t)$. This gives

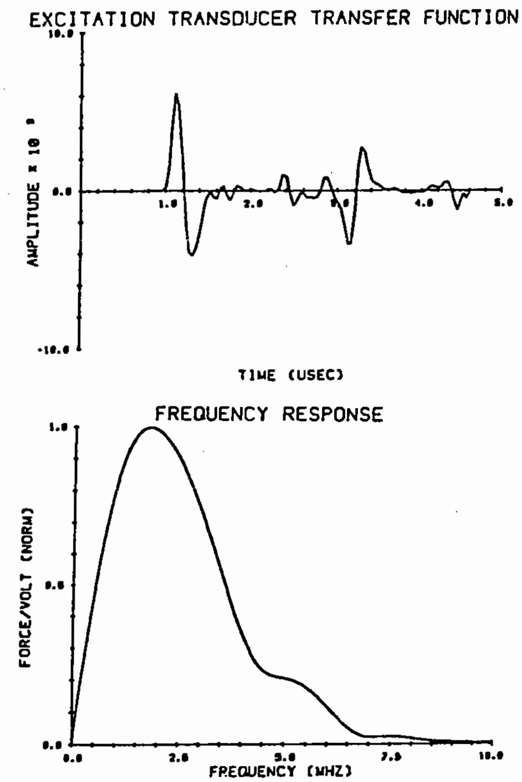
$$T_0(t) = [V_0(t) * G(t)]^{-1} * V(t) \qquad (6)$$

In applying Eq. (6), the inverse of the excitation voltage signal and the appropriate specimen impulse response are convolved with the signal detected by the receiving transducer which was again a displacement sensor. The device shown in Figure 6 incorporates the above ideas. It consists of a flat plate with a displacement sensor attached. It has been used in the transducer transfer function determination of several transducers. The transfer function determined for one broadband transducer is shown in Figure 7(a) and its corresponding frequency characteristics are in Figure 7(b). It is noted here that the vertical axes are in units of [Force/Volt].

To verify whether the transducer transfer function so obtained is correct, it was used to

Figure 6 - Transducer Calibrator device.

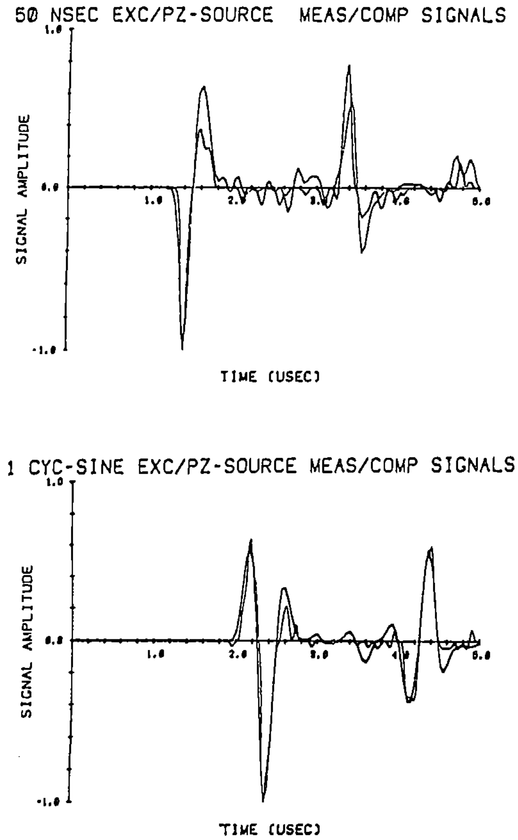




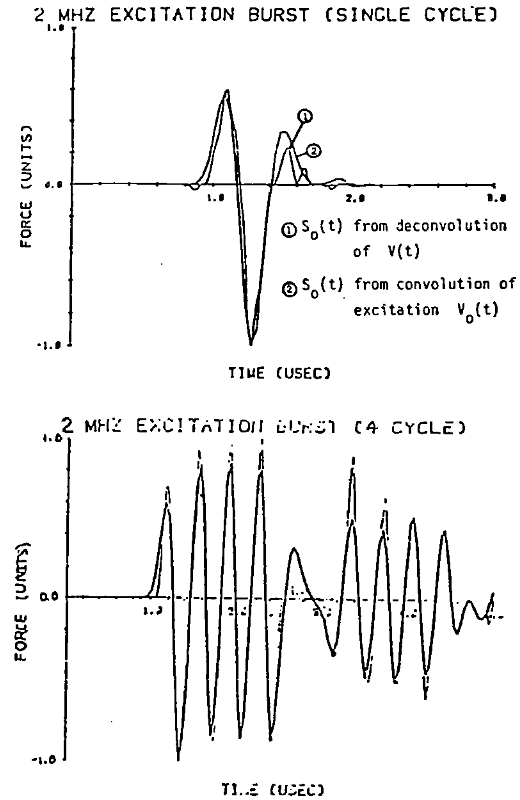
Figures 7(a) and 7(b) - Source Transducer Transfer function.

predict the displacement signal with Eq. (1) corresponding to other (arbitrary) excitation voltage signals applied to the source transducer. Figures 8(a) and 8(b) show the comparison between the predicted and the measured voltage (displacement) signals when the excitation was a 50 nsec shock pulse and a single cycle of a 2 MHz sine burst respectively. As an alternate check, a comparison was made between the ultrasonic source function, $S_0(t)$, computed by the convolution equation of excitation voltage and source transducer transfer function (Eq. (5)) and the source function obtained by deconvolution of the received displacement signals (Eq. (4)). Figures 9(a) and 9(b) show this comparison for a single-cycle and a four-cycle 2 MHz sine burst excitation respectively.

Receiving Transducer Transfer Function - The determination of the transfer function for a receiving



Figures 8(a) and 8(b) - Measured and predicted signals detected from two excitation functions.

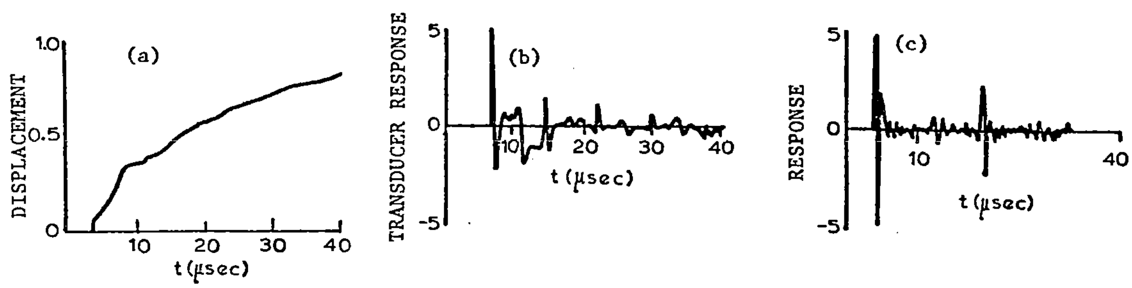


Figures 9(a) and 9(b) - Comparison between the transducer-generated force functions obtained by deconvolution and convolution due to various voltage excitations.

transducer can be obtained analogously as above. However, since the temporal characteristics of a particular source function may not be known *a priori*, two experiments can be performed using a fixed source and specimen. In the first experiment, the signal, $V_1(t)$, was detected at a particular receiver location with a known displacement (or velocity) sensor. From this, the inverse function $[S(t) * G(t)]^{-1}$ can be found. If the receiving transducer to be characterized is substituted in place of the displacement (velocity) sensor and the experiment repeated, the signal, $V_2(t)$, is produced. It follows then that the transfer function of the receiving transducer is given by

$$T(t) = A\,[V_1(t)]^{-1} * V_2(t) \qquad (7)$$

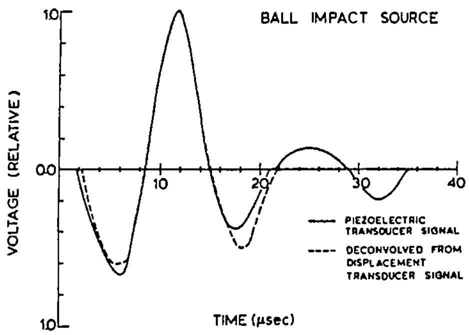
This procedure resembles that done in the frequency domain which has recently been used to determine the response of piezoelectric transducers to transient surface waves [7,8]. The results of experiments which illustrate the above are shown in Figures 10(a) - 10(c) which is taken from Ref. 4. Figure 10(a) is the measured epicentral displacement signal in an aluminum plate resulting from a mechanical step unloading excitation. Figure 10(b) is the signal measured with a 6.35 mm diameter broadband transducer mounted in place of the displacement sensor. Figure 10(c) is the result of the deconvolution, obtained through Eq. (7), which is the transfer function of the transducer operating as a

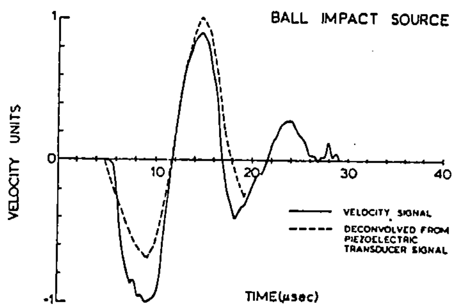


Figures 10(a) - 10(c) - Determination of a piezoelectric receiver's transfer function (a) Epicenter displacement, step-unloading source, (b) Piezoelectric transducer signal, step-unloading source, (c) Result of the deconvolution, T(t).

receiver.

As a check on the validity of the above procedure, another source was activated and the signals measured, in turn, by the displacement and piezoelectric sensor. By using the previously determined transfer function of the transducer (or its inverse) it is possible to convert one signal to another. Figures 11(a) and 11(b) show the results when this is done. In each case, a ball





Figures 11(a) and 11(b) - Piezoelectric transducer voltage signal measured by a displacement sensor, and actual voltage signal.
(b) Velocity signal measured by a piezoelectric transducer and actual velocity signal.

impact served as simulated source on an aluminum plate. Figure 11(a) shows the comparison between the detected piezoelectric transducer signal and the transfer function-converted displacement signal. The comparison between the measured velocity signal and the converted piezoelectric transducer signal into a velocity signal is shown in Figure 11(b).

CONCLUSIONS

It has been shown how a well-characterized ultrasonic system consisting of source, structure and receiver can be used to determine the ultrasonic pulse produced by a piezoelectric transducer operating under various excitation and coupling conditions. Based on the assumptions that the transduction characteristics of a transducer can be expressed as a transfer function, it has been shown how a well-characterized ultrasonic system can be used to experimentally determine the transfer function of a piezoelectric transducer operating either as source or receiver, thus establishing the relationship between electrical and acoustical quantities of the transduction process.

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