ULTRASONIC TRANSDUCER STANDARDS

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ABSTRACT

The piezoelectric transducer is the electromechanical conversion element in NDE. Existing transducers of this type are found to impose limits on the improvement in system performance and, at present, there is a lack of standards as required for calibration procedures. Physical "standards" based on equivalent circuits have been produced which model individual transducers, single transducers in pulse-echo mode and two-transducer configurations. The performance of these "standards" is shown to be in good agreement with that given by real transducers, and subject to less variability.

INTRODUCTION

Considerable advances have been made in the electronics that are now available for use in ultrasonic test equipment. Also, there is an increasing trend toward the application of digital signal processing in NDE, including the application of inversion algorithms for defect characterization. It is increasingly being found that it is the ultrasonic transducer, the electromechanical conversion element, which is imposing limits on the improvement of system performance and hence the development of quantitative NDE.

The operation of ultrasonic transducers based on piezoelectric elements, with structures as shown in Fig. 1, has been considered and reviewed by many authors, including Sachse and Hsu (1979). Such a transducer structure imposes severe limits on NDE system performance in terms of viewing angles, frequency/amplitude responses and artifacts introduced into the generated wavefield or received time-
domain signals. Within the framework of the present study, into
the observed non-ideal operation in these transducers (Bond, et al. 1981), it was found necessary to develop a "transducer standard"
to represent the first-order transducer characteristics. These
characteristics can be summarized as those due to

(a) The transducer radiating/receiving fields, which have
actions similar to a piston source (Freedman, 1970 and
Stepanishen, 1971).

(b) The piezoelectric element behaving similarly to an elec­
tromechanical resonator or waveguide (Redwood, 1963).

This paper presents "transducer standards" which have been produced
based on Mason's and Dotti's equivalent circuits. It has been
found that the resulting physical circuits provide reproducible ex­
perimental standards which can be used in

(a) the investigation of many of the variables associated
with actual transducers and the calibration procedures
which are applied to them;

(b) for the calibration of ultrasonic test equipment and the
inter-relationships between transducers and test equipment.

Individual transducers, transducers in pulse-echo and two-
transducer systems have all been simulated and preliminary results,
including some comparisons with results obtained with real trans­
ducers, are presented.
**Pulse-Echo Systems**

Many of the systems used in ultrasonic NDE are based on either (a) a single transducer used in pulse-echo operation, or (b) two transducers, one being the transmitter and the other the receiver. These basic systems are illustrated in Figs. 2a and 2b, respectively.

The systems shown in Figs. 2a and 2b can be considered in terms of a linear response model, where each element acts as a convolution on the initial impulse as it passes through the model. Such models have been described by several authors, including Newhouse and Ferguson (1977) and Stepanishen (1981) and such a system is shown in Fig. 2c, with the relationships between the initial impulse $x(t)$ and the final echo-signal output from the receiver $e(t)$ as:

$$e(t) = x(t) * A(t) * B(t) * C(t) * D(t) * E(t) + n(t)$$  \hspace{1cm} (1)

![Fig. 2. Single and Two Transducer Systems](image_url)

(a) single transducer in pulse-echo  
(b) two transducer transmit receive  
(c) block diagram representation of pulse-echo systems.
where functions relate to corresponding blocks shown in Fig. 2c, \( n(t) \) represents receiver amplifier noise and \( * \) a convolution. For single transducer systems used in pulse-echo configurations, \( A(t) = E(t) \), and for a perfect reflector \( C(t) = 1 \).

To a first order the components representing the radiating medium and scatter (monopole) can be represented by linear filters. However, the transducer transfer function is required to be more complex, due to the large number of variables involved. For the calibration of transducers or equipment, the items \( A(t) \) to \( E(t) \) in the expression (Eq. 1) need to be considered in more detail.

A transducer can be assumed to behave as a bandpass filter when the electromechanical conversions are performed. For such a circuit a network transfer function \( H(j\omega) \) can be defined (Javid and Brenner, 1963) as:

\[
H(j\omega) = \frac{V_{\text{out}}(j\omega)}{V_{\text{in}}(j\omega)}
\]

where \( \omega \) represents the frequency of the transducer, and \( V_{\text{in}} \) and \( V_{\text{out}} \) are the voltages seen at an electrical port and at an acoustic port (\( A \)), respectively. This system, which is considered as a black box with one electrical and two acoustic ports, is shown in Fig. 3.

**TRANSDUCER STANDARDS**

The operation of transducers, of the type shown in Fig. 1, can be represented by equivalent circuits such as those shown in Fig. 4. Of the circuits which have been proposed, probably the best known is that due to Mason (1948), of which a lumped parameter version as used by Stepanishen (1981) is shown.

When Mason's circuit, which is shown as Fig. 4b, is considered in detail, it is seen that it contains a negative capacitance. The introduction of a negative capacitance in a physical model based on such a circuit would involve the use of various active components, so the effect of this capacitance was investigated.

It has been reported that the negative capacitance is important for models of transducers where the electromechanical constant \( (k_T) \) of the piezoelectric material is high, such as for PZT5A (e.g., \( k_T = 0.486 \)). The presence of this capacitance leads to a shift in both the electrical and the mechanical resonance frequencies of such transducers (Fillipiczynski, 1975).

The magnitude of the frequency shifts was calculated, using the transfer function for the system shown as Fig. 3, given as Eq. 3.
Fig. 3. The transducer represented as a three port "black box" with a transfer function $H(j\omega)$.

Fig. 4. The Single Transducer Equivalent Circuits Investigated.
(a) Dotti's (1975) circuit
(b) Mason's lumped parameter model used in the computer model
(For these circuits, the electric field is parallel to the ultrasonic wave propagation in an equivalent transducer.)
\[
\frac{V_{\text{out}}}{V_{\text{in}}} = N\omega (-B^2 \sin t \cos t - \sin t (\cos t-1)+j((\cos t-1)B \cos t-B \sin^2 t)
\]

\[
(\cos t(B+A)(\cos t-1-\omega XcZcsin t) - \omega XcZcB \sin t \cos t + t \omega B \sin t)
+ (\cos t-1)(B \cos t + A(-B \sin 2 t)
+ j\{\sin t(I+AB) \cos t-1-\omega XcZcsin t
+ \cos t(A+B)B \omega XcZccos t+B \sin t(B \cos t+A)
+ \sin t(\cos t-1)\})
\]

where \( t = 2\pi x/\lambda \), \( x = \) transducer thickness in meters, \( \lambda = \) wavelength in meters. \( N \) is a normalizing constant and \( \omega = 2\pi f \) where \( f \) is frequency, frontface impedance \( Z_A = A \ Z_c \), and backing impedance \( Z_B = B \ Z_c \).

This transducer transfer function \( (V_{\text{out}}/V_{\text{in}}) \) is obtained by applying Kirchoff's voltage law to the circuit using the lumped parameter model as shown in Fig. 4b (Stepanishen, 1981). It is assumed that \( V_{\text{in}} = 1 \), i.e., the input impulse is an idealized impulse of infinite frequency spectrum and amplitudes at all frequencies is 1. The transfer function of the circuit was calculated for 2.2 MHz transducers using data given in Table 1 with various impedance backings. Results both with and without the negative capacitance are shown in Fig. 5.

Table 1. Data Used in Computer and Circuit Simulation

<table>
<thead>
<tr>
<th>Material</th>
<th>PZT5A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Impedance</td>
<td>33.7x10^6 kg/s m^2</td>
</tr>
<tr>
<td>Piezoelectric h constant</td>
<td>21.5x10^8 N/m</td>
</tr>
<tr>
<td>Piezoelectric thickness coupling (k_t)</td>
<td>0.486</td>
</tr>
<tr>
<td>Acoustic impedance of water</td>
<td>1.49x10^6 kg/s m^2</td>
</tr>
<tr>
<td>Transducer frequency (physical circuit)</td>
<td>2.77 MHz</td>
</tr>
<tr>
<td>Transducer diameter</td>
<td>35 mm</td>
</tr>
<tr>
<td>C_0</td>
<td>4700 pF</td>
</tr>
<tr>
<td>Negative Capacitance = -1/h^2C_0</td>
<td>-0.46 pF</td>
</tr>
</tbody>
</table>

*Data from Kossoff, 1966.*

In Fig. 5, the harmonic content of the responses is shown with the same amplitudes as the fundamental. However, the bandpass characteristics and increase in bandwidth for high impedance backing of the transducer is clearly illustrated.

It is observed that for PZT5A data, the values of the thickness coupling (k_t), are such that the negative capacitance contributes only marginally to the idealized response.

A complete description of the spectrum requires the frequency dependent amplitude response to be included. When the situation of
Fig. 5. The Transfer Function for Mason's Circuit with and without the Negative Capacitance Calculated at 2.2 MHz.
(a) Perfect backing, $Z_b = Z_c$
(b) Poor matching, $Z_b = 0.3 Z_c$
and for all cases, the amplitudes are normalized.

Impulse excitation is used in NDE, with a typical width of 4 $\mu$ sec, the effect of the negative capacitance can still be assumed to be small. It was, therefore, neglected in the initial physical simulations of the equivalent circuit.
PHYSICAL CIRCUIT

Circuits were constructed based on both Dotti's (1975) and Mason's (1948) transducer equivalent circuits. The parameters of primary interest being the responses obtained at the electrical port (E) and the acoustic port (A) (for the system shown in Fig. 3) corresponding to the electrical connection and the acoustic output at the transducer, respectively. The other acoustic port (B) corresponds to the backing layer, which can be varied. The results obtained were compared with those given by calculation and experiments.

DOTTI'S CIRCUIT

The equivalent circuit given by Dotti (1975) for the simulation of the system impulse response (shown as Fig. 4a), was constructed with a frequency of 0.8 MHz, which requires a 1.2 μsec delay. IC amplifiers (Type 741, 741S or 531), together with the necessary frequency compensation and color-TV delay lines of 0.6 μsec delay were used.

With this physical circuit, the electrical port (E) response was found to be in agreement with those computed and given by Dotti (1975), and is shown in Fig. 6. Outputs were also investigated at the acoustic port (A); however, in this model these are not valid.

MASON'S CIRCUIT

Due to the limitations encountered with Dotti's model, consideration was then given to the traditional Mason's (1948) circuit. As already considered, the construction of a physical version of the complete equivalent circuit is complex, requiring active devices, due to the presence of negative capacitance. The circuit without the negative capacitance is readily constructed and this simplification would appear to be valid. The simplified circuit is exactly analogous to a piezoelectric bar (Redwood, 1961), and it can be used to demonstrate the first order transducer characteristics. Redwood (1964) considered this circuit and has given results for a physical circuit operating at 6 KHz. In the present study, the frequency range of interest is 1.0 to about 10.0 MHz, and various circuits corresponding to transducers in that range have been constructed.

A typical example was for a transducer with a frequency of 2.77 MHz, with circuit parameters $C_0 = 4700 \text{ pF}$, $hC_0 = 10$ and using lengths of 50 ohm delay line. As the circuit was constructed using low impedance lines, it enabled initial investigation of system response to be performed using a low voltage (5-10 volt) Hewlett-Packard pulse generator. The system impulse response and corresponding spectrum, at the electrical port, was in close agreement with the Dotti model, shown as Fig. 6.
Examples of the output obtained with the physical circuits at the acoustic port (A) for variable backing (damping), all for the 10.0 volt peak to peak input are shown in Fig. 7, and the corresponding spectra are shown in Fig. 8.

It is seen in Fig. 7b that a small oscillation is produced in addition to the single cycle, and this is due to the finite inductance of the transformer used. This feature agrees better with real transducers than the theoretical computer model responses. It is also seen, in Fig. 8a, that the resonant peak is found at 2.2 MHz. This observed shift in frequency from the designed response of 2.77 MHz is similar to that found when damping is added to real PZT discs in transducer fabrication. A further shift in frequency of about 0.2 MHz is observed for cases of high damping, as seen in Fig. 8b. The insertion loss for the single transducer standard is approximately -20 dB.

An increase in 3 dB bandwidth is given with improved matching in the backing; this is clearly illustrated in Fig. 8.

Within these experimental limits, the physical circuit results are in agreement with theory and, in general form, those given by Redwood (1964) for measurements made at 6 KHz.

To provide the full physical circuit, as described in the Mason's model (Fig. 4b), the inclusion of the negative capacitance was investigated. The design produced proved to be unstable and subject to oscillation at a range of resonant frequencies. The overall response given was found to give no improvement over that obtained with the basic physical circuit.
Fig. 7. Time Domain Waveforms at Port A Obtained for Mason's Circuit with Coupling to Water.
(a) \( Z_b = 0.2 \, Z_c \) and (b) \( Z_b = Z_c \).
(Scales: Horizontal = 0.5 \( \mu \)s/div, Vertical = 0.1 V/div)

NDE SYSTEM SIMULATION

To provide useful "standards," it is necessary to consider extending the operation of the physical circuits to cover complete pulse-echo and two-transducer configurations. To a first order model, the transducer generated/received wavefields can be considered to be that due to a piston in a baffle. When such a structure is impulsively excited, the wavefield consists of two waves, with difference characteristics, these being the plane and the edge waves. The results obtained from the Mason's models and shown in Figs. 7
and 8 consider only the plane wave component resulting from the motion of the transducer (piston) face. The edge wave is generated at the circumference of the transducer, and is due to the relative motion of the transducer and the baffle. The edge wave follows the plane wave in the nearfield and is superimposed in the farfield for a transmitter (Weight and Hayman, 1978), as illustrated in Fig. 9a.

The physical circuit used to add the edge wave was a delay line as shown in Fig. 9b. For the simulation of the on-axis wavefields the length of the delay used is longest in the nearfield and reducing
Fig. 9. Simulation of the Near and Farfield Cases for a Piston Radiator of Finite Dimensions.
(a) illustration of the near and farfield cases, and (b) circuit used in the simulation.

to one half period of the plane wave in the farfield. Examples of the nearfield and farfield situations are shown in Figs. 10a and 10b. The maximum delay required is the propagation time of a Rayleigh wave from the transducer edge to axis. The single spike or half cycle in the nearfield is achieved by completely matching the front and backface impedances.
Fig. 10. Results Obtained with the Physical Circuit.
(a) nearfield, and (b) farfield.
(Scales: (i) and (iii): Horizontal 0.5 s/div, Vertical = -0.1 V/div.
(ii) and (iv): Horizontal = 500 KHz/div, Vertical = 10 dB/div.

PULSE-ECHO SYSTEMS

Complete NDE single and two transducer systems have been simulated in physical circuits. The first case considered, and shown in Fig. 11a, was for a compression wave transducer used in pulse-echo mode in water, using a flat metal reflector. The time-domain and corresponding spectra for both the physical circuit and a
Fig. 11. Simulation of the Single and Two Transducer Pulse-Echo Systems.
(a) single transducer using a Panametrics 5052PR pulser/receiver
(b) two transducer using an intermediary delay line.

real transducer, for reflection at 9 cm depth are shown in Fig. 12. In both cases, a Panametrics 5052PR Pulser/Receiver and gate 5052G with the same settings were used. It is observed that under certain circumstances with high impedance backings, there is considerable harmonic generation when the physical circuit is used in this pulse-echo mode, compared with its own basic acoustic port output. These effects are observed to be related to the characteristics of the input pulse used.

The second case considered, and shown as Fig. 11b, was for two 2.2 MHz transducers and using a Hewlett-Packard pulse generator, for plane wave transmission between them through water. For the case of circuits with identical parameters, including the same value for the backing impedance, the system gives results which are identical to those obtained in pulse-echo operation, and results similar to those shown in Fig. 12 are obtained. The results for this system, for example, with different backings on each transducer, are shown as Fig. 13.
Fig. 12. Simulation of Single Transducer in Pulse-Echo.
(a) simulated time- and frequency domain
responses (plane wave only),
(b) results for a 2.25 MHz transducer with
the same control settings as for (a).
A Panametrics 5052PR pulser/receiver and 5052G
stepless gate is used. Energy = 3, 20 dB gain
and damping control set at 10.

EXTENDED SIMULATIONS

For the design of any inspection system to be optimized, it is
necessary to extend the conceptual framework used to describe such
systems, to include such items as the band-limiting properties of
the material under test, the frequency response of the flaw, and
Fig. 13. Two Transducer Results for 2.2 MHz Equivalent Circuits, where $B_1$ and $B_2$ correspond to backing impedance of the transmitting and receiving transducers, respectively. 
(a) $B_1 = 0.8 \, Z_c$, $B_2 = 0.4 \, Z_c$, and (b) $B_1 = 0.4 \, Z_c$, $B_2 = 0.6 \, Z_c$.

The detail of the transducer frequency response. The concept of "measurement window" has been introduced by Thompson (1981), and it is found that for flaws at a particular depth in a particular material, only certain frequencies can be used in the measurement. These characteristics can be introduced in physical standards by use of filters added to the acoustic port output of the physical circuit. A complete extended two-transducer system, neglecting the radial and edge wave responses of the receiver, is shown in Fig. 14.
Fig. 14. The complete extended two transducer system under investigation. The system gives both on and off-axis wavefields and includes "measurement window" parameters.

The physical circuits introduced in this paper can also be extended to cover off-axis wavefields, and an additional equivalent circuit is being used to include a representation of radial modes, as shown in Fig. 14.

CONCLUSIONS

It has been shown that physical circuits based on equivalent circuits of a transducer can be produced to provide "ultrasonic transducer standards," and that the circuits can be extended to provide simulation of NDE inspection configurations.

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