METHODS OF MEASURING ELECTRICAL CHARACTERISTICS OF ULTRASONIC DELAY LINES

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Summary -- This paper is concerned with methods of measuring useful electrical characteristics of ultrasonic delay lines employing piezoelectric transducers. The impedance characteristics of delay lines are discussed by means of an equivalent circuit representation, the advantage being that it presents the essential impedance variations of the line in terms of quantities that are directly measurable by an admittance bridge. Measurements of insertion loss and the determination of band-pass characteristics are carried out by the use of a conventional loss-measuring circuit. In regard to this type of measurement, the recent development and use of short delay lines (delay times of 50 μsec or less) with ceramic transducers requires the consideration of certain measuring problems resulting from the low loss in the line and the high electromechanical coupling of these transducers. It is shown that the measurement of unwanted signals arising from the sonic pulse making multiple path traversals requires special care because the input as well as the output termination affects the measurement. Sample results obtained for various types of measurements are given using data from experimental delay lines having ceramic transducers bonded to fused quartz. However, all the measuring techniques discussed may be applied to lines using quartz crystal or other piezoelectric transducers.

INTRODUCTION

As most frequently used, delay lines consist of an input transducer, a delay medium and an output transducer. The physical sizes and shapes of delay medium and transducers and the mode of motion used in the transducers vary depending upon the delay time and other considerations, but usually the arrangement of transducers is symmetrical.* Whether or not the arrangement of transducers is symmetrical, a delay line having separate input and output transducers is, from the circuit point of view, a four-terminal network. Associated with such a network are several important electrical quantities which are measurable for any particular delay line and which may be used to characterize its performance. These are (1) input and output impedances, (2) insertion loss, and (3) the level of unwanted signals relative to the main delayed signal at the output terminals. Each of these three types of quantities is measurable as a function of the carrier frequency of an input rf pulse. In any specific application of an ultrasonic delay line, these quantities provide a circuit designer with the information he needs to know in order that both the line and its associated circuitry may be used under optimum electrical operating conditions.

The frequency dependence of the impedance and loss characteristics for the four-terminal network representing a delay line may be given in terms of an equivalent circuit. W. P. Mason\(^1\) has derived an equivalent network of fixed, lumped circuit elements representing transducers. Applications of this network to the

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\* The term symmetrical is meant to designate that the input and output transducers have the same dimensions and that the bonding between transducers and delay medium is the same.
analysis of band-pass characteristics of delay lines using quartz crystal and ceramic transducers have been made by several authors.2-4 The elements used in the equivalent circuits depend on the elastic, piezoelectric and dielectric constants of the transducer and bond materials, the mode of motion and the elastic properties of the delay medium. While this type of equivalent circuit is useful in theoretical analyses, usually not all the pertinent constants will be known in the case of a specific delay line; consequently, it is desirable to have an equivalent circuit involving only experimentally determinable quantities.

In most applications, ultrasonic delay lines are used with pulses short enough so that the operation of one transducer is not affected by the way in which the other transducer is terminated. Hence each transducer can be considered by itself as a two-terminal device for which, at any arbitrary frequency, the impedance or admittance may be measured by various means. Because either impedance or admittance is a complex quantity, a complete specification involves two quantities; i.e., either a magnitude and a phase angle or a resistive and a reactive component. For this reason an experimentally determinable equivalent circuit involves basically two circuit elements which have frequency dependent values.

The equivalent circuit for a receiving transducer differs from that of a transmitting transducer in that an ideal voltage source, the magnitude of which is frequency dependent, is required in addition to the two frequency-dependent circuit elements. An example of such an equivalent circuit is shown in Fig. 1. For a symmetrical delay line, the input and the output transducers are represented by the same functions $R_E(f)$ and $C_E(f)$. The two circuits differ only in that for the output transducer an ideal voltage source has been inserted in series with the parallel combination of $R_E(f)$ and $C_E(f)$. The output circuit is the equivalent of the receiving transducer, according to Thevenin's theorem. $E_{oc}(f)$ is the open circuit voltage at the output terminals, and in general, it is a quantity that will depend on the circuit to which the input transducer is connected as well as the inherent properties of a particular delay line (e.g., length of path, nature of bonding between transducers and delay medium, backing of transducers). Though $E_{oc}(f)$ could be measured and plotted graphically for any given line, it will not be of particular interest to the circuit designer who is primarily concerned with the impedance and insertion-loss characteristics of a particular delay-line design.

The form of the equivalent circuit for a delay line as given in Fig. 1 is a reduction to two variable elements of the more general equivalent circuits discussed by Mason and others.1-4 In representing a delay line by the reduced form of equivalent circuit, the primary advantages gained are: (1) the impedance characteristics of a specific delay-line design are presented by two functional quantities which may be experimentally determined, and (2) the information on impedance variations with frequency is presented in a form more directly useful to the circuit designer.

**IMPEDEANCE MEASUREMENTS**

A General Method

$R_E$ and $C_E$ may be determined by using an rf admittance bridge which, at an arbitrary frequency, determines the electrical characteristics of a transducer in
terms of a parallel combination of resistance and capacitance. When measured at a number of frequencies, the values obtained for these quantities can be graphed, and the resulting curves define $R_E(f)$ and $C_E(f)$. For a symmetrical delay line the average curves based on the data from both transducers may be used as the $R_E(f)$ and $C_E(f)$ characterizing the line. It may be noted that the results for these two quantities depend not only on the transducer material but also on the delay medium and on the layers of electrode and bonding materials.

Because reflected elastic waves returning to a transducer being measured alter its admittance, a measuring circuit of the type shown in Fig. 2 is required.
The circuit is designed so that the input pulses are long enough to permit the admittance to be measured under conditions of steady-state vibration, but short enough so that reflected pulses do not interfere. The minimum length of pulse required will depend on the type of transducers and their loading. For example, in the case of ceramic transducers bonded to fused quartz and operating at 15 mc, a pulse width of 1 to 3 \( \mu \)sec is long enough. The exact form of the bridge will depend on the type of transducers measured and the precision desired. A bridge used to measure ceramic transducers in the range of 10 to 30 mc is shown in Fig. 3.

![Circuit Diagram]

**Fig. 3 - Bridge circuit used for measuring electrical characteristics of transducers.**

**Typical Data and Interpretation**

The forms of the functions \( C_E(f) \) and \( R_E(f) \) for the specific case of a delay line using barium titanate ceramic transducers* are shown in Fig. 4. The curves

*Throughout this paper the words barium titanate ceramic are used to designate a material which on a weight basis is 80% BaTiO\(_3\), 12% PbTiO\(_3\) and 8% CaTiO\(_3\). The transducers referred to were disk-shaped, having a diameter of 0.250 inch. The upper surface was partially covered by a silver electrode 0.218 inch in diameter; the lower surface was completely covered. The completely electroded surface of each transducer was bonded to the silvered surface of a fused quartz by a low-melting-point solder.
The curves $C_E(f)$ and $R_E(f)$ for a delay line using barium titanate ceramic transducers.

1. The mechanical or series resonant frequency of the bonded transducers is determined by the minimum of the resistance curve.

2. The shunt capacitance of the transducers is the value of $C_E(f)$ at the series resonant frequency. This is the capacitance which is usually tuned out under operating conditions by an inductor in parallel with the transducer. When the shunt capacitance is antiresonated by a parallel coil, the input impedance at the series resonant frequency is given by the minimum of the resistance curve (assuming a high Q coil).

Figure 4 also shows an equivalent circuit involving fixed elements which may be used to represent the transmitting transducer in the neighborhood of resonance. The admittance characteristics calculated from this equivalent circuit are shown by the dashed line. The method of determining an equivalent circuit involving fixed elements is discussed in another paper.

Curves similar to those shown in Fig. 4 may be obtained for lines using quartz crystal transducers. The main differences in this case result from the considerably lower electromechanical coupling of quartz transducers. In particular, the minimum resistance of the $R_E(f)$ curve is considerably higher (several thousand ohms on the average), and $C_E(f)$ is constant within a few per cent across the entire band.
A Loss Comparison Circuit

The insertion loss* of a delay line under specified termination conditions may be conveniently measured by means of a conventional loss comparison circuit of the type shown in Fig. 5. The circuit consists of two branches. One branch contains the network under test, and the other branch contains a step attenuator by means of which a known amount of loss may be switched into the circuit. The output signals of the two branches are compared and the attenuator is adjusted until their amplitudes are the same. When this condition is obtained the inser-

*Insertion loss is defined for a given three or four-terminal network connected between a specific source of internal impedance $Z_S$ and a specific load of impedance $Z_L$. If $P_1$ is the power delivered by the source to the load when they are directly connected, and $P_2$ is the power delivered to the load when the network is inserted between the source and the load, the insertion loss in decibels is $I.L. = 10 \log_{10} \frac{P_1}{P_2}$. 

Fig. 5 - A circuit for measuring the insertion loss of a delay line operated with an input termination $R_s$ and an output termination $R_L$.
tion loss of the delay line operating between impedances Rs will be equal to the loss indicated by the attenuator if

\[
\frac{R_{SA}}{R_{LA}} = \frac{R_s}{R_L}
\]

and

\[
R_{LA} = \text{the iterative impedance of the attenuator.}
\]

An important feature of this circuit is that as long as conditions (1) and (2) are met, the attenuator reads insertion loss correctly regardless of the impedance of the source driving the measuring circuit.

A series or parallel coil is usually used in the input and output circuits of a completed line in order to resonate or antiresonate the shunt capacitance at the midband frequencies. These coils will be considered as part of the delay line assembly. The circuit of Fig. 5 permits a delay line assembly to be measured under a wide range of termination conditions, but usually the loss measurement of most interest is that in which Rs and Rl correspond to the terminations of intended use.

The measuring procedure for insertion loss as discussed in the preceding paragraphs is based on the use of a steady-state sinusoidal signal input. The same procedure is applicable to pulsed delay lines under the condition that the input pulse be long enough such that the transducers have time to reach a condition of steady-state vibration. If this condition were not imposed, one might expect the measured value of the insertion loss of a delay line to depend on the amplitude of the applied signal. In practice, signals consisting of rf bursts have been observed to come up to their steady-state amplitude within approximately 2 to 3 cycles when ceramic transducers are operated in the range of 10 to 20 mc.

Thus in this case a pulse only 0.5 \mu s long is long enough to permit the insertion loss to be measured and be independent of the amplitude of the input pulse over a wide range in signal level.

Typical Loss Data

Figure 6 shows the band-pass characteristics of a short fused quartz delay line (approximately 2 \mu s delay time) using the same ceramic transducers as those from which the data in Fig. 4 were obtained. These curves show the results obtained by using parallel coils to antiresonate the shunt capacitance at the series resonant frequency, 15.5 mc, and by using symmetrical resistive terminations of the values indicated on the graph. The loss measuring circuit in Fig. 5 was used in taking these measurements.

Comments on Loss Measurements

A common practice in the case of long delay lines using quartz transducers has been to measure insertion loss under conditions of zero input termination and some nonzero output termination. The circuit shown in Fig. 5 could be used in
Fig. 6 - Band-pass characteristics of a delay line assembly using ceramic transducers.

this way by making \( R_s = R_{SA} = 0 \) and letting \( R_L \) have any desired value.* \( R_LA \) must always be equal to the iterative impedance of the attenuator. While there is nothing incorrect in this procedure, there are several undesirable consequences:

1. Because a delay line in actual use will be driven by a source having a finite internal impedance, the loss and band-pass characteristics measured will not be those corresponding to the conditions of use.

*Sometimes the circuit in Fig. 5 is used with \( R_s = 0 \) and \( R_{SA} \) equal to some high value of resistance. This is done to increase the load impedance seen by the source driving the circuit. The insertion loss curve obtained in this manner is the same as that obtained for the condition of zero input termination and an output termination equal to \( R_L \), except that the numerical values of the attenuator readings are now decreased by a constant amount \( N \), given by

\[
N = 10 \log_{10} \left( \frac{R_{LA}}{R_{SA} + R_{LA}} \right)^{-2}
\]
(2) Low-loss lines measured in this manner may show an insertion gain, depending upon how large $R_L$ is relative to the impedance of the transducer.

The latter statement may seem at first surprising, but the theory indicates that for a line having ideal transducers and operated at the midband frequency, the limiting value of the output voltage, as $R_L$ becomes large, is twice the value of the voltage across the input transducer.\textsuperscript{37} Short lines using ceramic transducers of the type used for the data of Figs. 4 and 6 have shown small insertion gains when measured between zero input and 100 ohms output terminations.

MEASUREMENT OF UNWANTED SIGNALS

Types of Unwanted Signals

The main pulse out of a delay line is accompanied by various types of unwanted signals which may arrive ahead of or behind it. These unwanted signals appearing in the output may be classified into three types:

1. An undelayed signal resulting from the direct electrical feed-through of a portion of the input pulse.

2. Signals arriving before or after the main pulse caused by the spreading out of the sonic beam and, consequently, portions of it taking paths through the line other than that followed by the main signal.

3. Signals resulting from a portion of the main pulse making multiple traversals of the path between input and output transducers. In general, the electrical termination of the output transducer is not such as to result in complete absorption of the energy in the incident sonic pulse. Consequently, part of the pulse travels back and forth until all the energy is dissipated in the termination of the input and output transducers and in the delay medium itself.

The level of any unwanted signal is conveniently measured by the circuit in Fig. 5. For a particular unwanted signal, the loss of the calibrated attenuator is increased until the pulse amplitude from this branch corresponds to the pulse amplitude of the particular unwanted being measured. The difference between the level of the main pulse and the final attenuator reading corresponds to the number of db by which the unwanted signal is below the main signal. Ordinarily this measurement is made only on the strongest unwanted signal at each frequency for which the loss is measured.

Variation in the Level of Type 3 Unwanted Signals Depending Upon the Effective Input Termination For Reflected Pulses

The pulse nature of delay line applications introduces a complication into the measurement of power levels of the unwanted signals relative to the main delayed signal. This complication is the effect of the internal impedance of the driver upon the input termination of a delay line as seen by reflected pulses arriving at the input transducer. To demonstrate the effect, the following experiment was devised.
A 2.0 \mu\text{sec} delay line was connected between terminating resistances of 30 ohms, as shown in the circuit in Fig. 7. The coils in the input and output circuits of the delay line were tuned for maximum output of a pulse with a 15 mc carrier frequency. A resistance \( R_d \) was connected in series with the output of the driver stage. When \( R_d \) was varied, the insertion loss of the line remained constant at 5 db because the same reference voltage \( E_R \) was shared by both branches; however, the unwanted signals varied in both level and form. In the graph in Fig. 7, data for the variation in the level of the first and second unwanted pulses are shown. These unwanted signals correspond to what are frequently called "third-time through" and "fifth-time through" signals. The data in this particular case show that for a low value of \( R_d \) the third-time through signal was the stronger unwanted. As the value of \( R_d \) was increased, this signal became weaker; and above a value of 20 ohms, the second unwanted was the stronger of the two. As a result of this type of behavior, there is generally an optimum termination producing a minimum level for the unwanteds when the main unwanteds are those caused by multiple path traversals of the sonic pulse.

\[
\begin{align*}
\text{Fig. 7 - Variation in the level of unwanted signals with resistance } R_d. \\
\end{align*}
\]

This was not the same line as that which was used for the data shown in Figs. 4 and 6.
Figure 8 is a photographic record of the form of the output pulses under the indicated test conditions as seen on the face of an oscilloscope. The signals shown are the envelopes of the detected rf pulses. The vertical deflection is proportional to their amplitude and the horizontal deflection increases linearly with time. On the records, a large division in the horizontal direction corresponds to $5 \mu$s/sec. The upper picture shows the output pulse when $R_D = 0$; in addition, the first two unwanted signals are visible. In the case of the middle picture all conditions are the same as for the upper except that the signal into the delay line has been increased making the unwanted signals more visible. The increased level caused the main signal to go off scale. The lower picture shows the change in the level and form of the first unwanted pulse when $R_D$ was increased to 200. (The signal output of the driver was, of course, increased to compensate for the drop resulting from the increased value of $R_D$.) It should again be emphasized that although the level and form of unwanted signals were altered by the changes in $R_D$, the insertion loss for the main pulse remained the same.

The reason for the variation in the level of the unwanted signals can be made more apparent by considering the delay line and measuring circuit pictured in Fig. 9. The input transducer is excited by means of the rf pulse shown in the figure. This produces an elastic wave packet which travels through the delay medium with the appropriate elastic wave velocity. While the elastic pulse is traveling through the line, the input signal drops to zero. When the elastic
pulse arrives at the receiving transducer, part of its mechanical energy is converted into electrical energy which is dissipated in the load resistance $R_L$. Part of the elastic wave motion is reflected back to the input transducer (partly because the receiving transducer does not cover the whole reflecting surface and

![Diagram](image)

\[ Z_{TRP} = R_S + \frac{Z_G (R_{SA} + R_{LA})}{Z_G + R_{LA} + R_{SA}} \]

\( \text{(Input Termination for Reflected Pulses)} \)

In this equation $R_{LA}$ is the iterative impedance of the step attenuator.

The preceding discussion takes into account the fact that the amplitude of a pulse reflected from a surface with a transducer on it depends appreciably on the electrical termination of the transducer. That this is the case for short delay lines using barium titanate transducers is demonstrated by the data shown in Fig. 10. These data were obtained using the barium titanate transducers (approximately 1/4 inch in diameter and resonant near 15 mc) on the same short delay line used in obtaining the data shown in Figs. 7 and 8. The line was operated as a single-ended delay line; in each case the same transducer was used for transmitting and receiving. The second transducer on the reflecting surface was terminated in a coil (used to antiresonant the shunt capacitance of the transducer at 15 mc) and a variable resistance $R_T$. The data show the power level of the output pulse relative to the input signal as a function of the value of $R_T$ for the two different
cases. The transducers on the delay line were designated A and B and were connected as indicated in the circuit shown in Fig. 10. In each case the termination conditions at the input circuit were held constant, so that the indicated variations depended only on the changes in the terminating circuit of the reflecting transducer.*

The variation in the form and level of the reflected signal with changes in the value of $R_T$ are shown by the photographic records in Fig. 11. The top picture shows the form of the input and reflected pulses observed on the oscilloscope when $R_T = 0$. The middle record shows the change produced in the received signals by changing $R_T$ to 75 ohms, keeping the input level the same. The bottom photograph shows the appearance of the output signal when the input signal was increased enough to make the reflected pulses clearly visible. The photographs were taken for the case in which transducer B was reflecting. For this transducer, the data in Fig. 10 indicate that at 75 ohms the reflected signal is a minimum. The record shows that the first reflected pulse has an initial and trailing transient separated by a minimum which was found to be extremely sensitive to small changes in $R_T$ and $L_T$. The cause of these transients is interpreted to be the changes in the effective impedance of the transducer when its vibration is started or stopped.

A Modification of the Basic Measuring Circuit Permitting Complete Specification of the Input Termination

For measuring purposes it is desirable to have a means of specifying completely the input termination of a delay line. In the measuring circuit of Fig. 5 the input termination of a delay line, from the point of view of reflected pulses incident upon the input transducer, includes the impedance of the driver. Usually this impedance has a complicated dependence upon frequency and may vary considerably depending upon whether or not the driver is turned on or off. A way of eliminating this complication is to tie down the impedance to a small enough value so that it becomes negligible compared to $R_S$ (see Fig. 9). When $Z_G$ is thus made small, the input termination is practically the same for reflected pulses as for the initial input pulse. For example, in a specific case in which $R_S = R_L = 75$ ohms and $R_A = R_A' = 50$ ohms, $Z_{ITRP}$ can range in magnitude from a minimum of 75

*The circuit arrangement used to obtain the data in Fig. 10 may be generalized to measure completely the effective internal impedance of a transducer when used as a receiving device. If we assume that a minimum reflected signal corresponds to the condition of a maximum power transfer from the reflecting transducer to the load, then the maximum power transfer theorem requires that the impedance of the external load be the complex conjugate of the source impedance. Thus, at any frequency $L_T$ and $R_T$ can be varied to obtain a minimum reflected pulse, and from these quantities the effective internal impedance of the reflecting transducer can be computed.

W. G. Cady has treated theoretically the problem of the effect of the electrical load of a receiving transducer upon the amplitude of the reflected elastic wave. He finds that for an ideal thickness-mode transducer terminated in the complex conjugate of its internal impedance, the voltage generated across the transducer by the received energy leads to the emission of a wave of equal amplitude and opposite phase as the reflected wave, resulting in complete cancellation of the reflected wave.
Fig. 10 - Variation in level of received reflected pulse depending upon resistive termination of the reflecting transducer.

Fig. 11 - Photographs showing variation in amplitude of received pulses depending upon resistive termination of reflecting transducer.
ohms to a maximum of 175 ohms, depending upon the value of $Z_0$. A value of $Z_0$ equal to 5 ohms would result in an input termination of approximately 80 ohms for all reflected signals, and consequently the input termination can be considered to be 75 ohms for most purposes.

An example of a driver circuit having an output impedance tied down to less than 5 ohms is shown in Fig. 12. This circuit may be used to deliver rf pulses as short as $1/2 \mu$sec with a peak-to-peak amplitude of approximately 1 volt. An output of this amplitude is ample for testing short delay lines. The driver has a usable level of output from 5 mc to 40 mc.

In addition to its low output impedance, a gated amplifier circuit of the type shown in Fig. 12 has several other advantages. The average power dissipated in the plate circuit is low because pulse durations are approximately $1/4$ sec and repetition rates range from 60 to 1,000 pps. In single-ended gated amplifier stages a pronounced transient caused by switching the plate current on and off is usually present, but this switching transient is cancelled out by the push-pull design. An important limitation of this type of driver circuit is the fact that a small amount of the continuous input rf signal is fed through to the output. This feed-through may be a source of interference in the measurements of extremely low level unwanteds. For the circuit shown, it was possible to obtain at the output terminals a difference between the output level when the driver is turned on and the leakage rf level when it is off of the order of 60 db. This difference is great enough for most measurements involving short delay lines.
CONCLUSION

The preceding discussion has been based largely on experimental results from short delay lines using ceramic transducers. The same techniques of measurement may be applied to delay lines using quartz crystal transducers.

There are important differences between lines using quartz and ceramic transducers. For example, in lines using quartz transducers the capacitive component of the input admittance of a transducer may be satisfactorily represented by a fixed capacitor, whereas for lines with ceramic transducers the capacitive component may vary by 20 per cent or more. Another important point of difference is that of the effect of termination impedances on curves for both the loss in the main signal and the level of unwanted signals.

Delay lines using quartz crystals usually have impedances at midband of the order of thousands of ohms. In both measurement and use they are frequently deliberately terminated in impedances of the order of hundreds of ohms in order to widen their pass band. As a result of the large mismatch, small variations of the order of 10 to 100 ohms in the termination impedances make little difference in either of these two types of quantities. On the other hand, lines with ceramic transducers usually have low impedances of the order of 20 to 100 ohms at midband. In this case, variations of 10 to 100 ohms in termination impedances can make appreciable changes in measurements of both loss and unwanted signals, and the change in unwanted signals may be especially apparent if a line is short. The differences observed in the two types of delay lines are basically caused by the considerably higher electromechanical coupling factor of ceramic transducers.

BIBLIOGRAPHY


