the GENERAL RADIO Experimenter

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A NEW TYPE OF VARIABLE DELAY LINE

With the introduction of the new delay line described in this article, the realization of the complete line of General Radio components and instruments for pulse work is brought one step nearer. At the present time, complete data are available on only one model, the Type 314-S86, but the design of a complete series of variable delay lines with maximum delays of 100, 200, 500, and 1000 millimicroseconds and characteristic impedances of 100, 200, 500, and 1000 ohms is now under way. For a given maximum delay, one or more lines will be offered to fulfill a customer's impedance or size requirements. The bandwidths per unit delay of the larger size units, in general, will be greater than those of the small units, and each delay line will be designed for optimum transient response.

These variable delay lines find general application as wide-band phase-shifting devices and can be used also as components in pulse and video-frequency systems, such as computers, radar and beacon systems, and TV equipment; in short, wherever it is desired to delay a wide-band signal without introducing phase distortion. It is probable that some particular impedance levels and delay times will be more useful than others, and inquiries from customers are invited concerning their preferred values of delay, impedance and bandwidth, even though these values may not be listed above.

In many applications, the most important attribute of an electromagnetic delay line is a satisfactory transient response. Since a good transient response results from the proper combina-

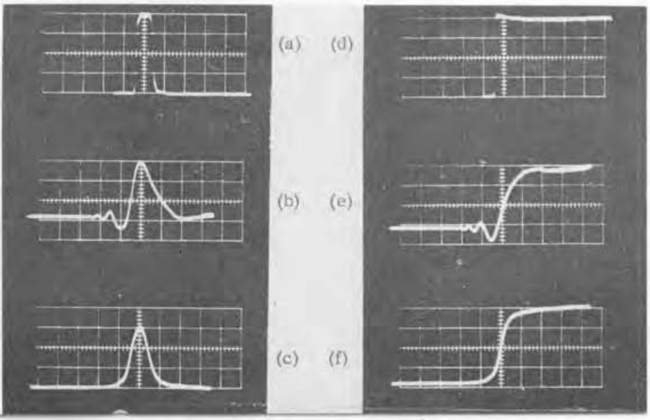

Figure 1. Pulse and step responses of 1-μsec delay, 500-ohm, variable delay lines. (a) pulse input, (b) pulse out of uncompensated line, (c) pulse out of skewed-winding line, (d) step input, (e) step out of uncompensated line, (f) step out of skewed-winding line. Scope photos taken on Tektronix 541, 0.1 μsec/cm sweep.

tion of a constant time delay (linear phase characteristic) with an adequate frequency response, delay lines exhibiting reasonable behavior with step or short-pulse excitation are usually well suited for other delay applications.

In the course of the development of the variable delay lines described here, a method of analysis was developed which sheds light on several properties of distributed-winding delay networks, including (1) the variation of time delay with frequency and (2) end effects. Further investigation along these same lines has already led to some interesting data on losses in distributed delay networks and, it is hoped, may lead to accurate methods for the calculation of such losses.

Because of the experience of the General Radio Company in the manufacture of wire-wound resistors and the availability of machines and components, it was possible to fit the design of the variable delay line into the same general form as that of a wire-wound potentiometer, with its obvious advantages of convenience, small size, and economy. Hence the inductance coil was developed on a card-type mandrel for winding on our standard winding machines.

When the first experimental variable delay lines of this type were constructed on potentiometer forms with copper wire instead of resistance wire and with the addition of a sheet copper-foil ground capacitance, the pulse and step responses of these lines (see Figure 1(b) and 1(e)) were very disappointing. After much experimental and analytical work, the present model variable delay line has been designed with skewed winding for constant delay as a function of frequency, and with tapered capacitance strips to reduce mismatch caused by end effects. The responses shown in Figure 1(c) and 1(f) are characteristic of the performance of these new delay lines.

The Delay Equalization Problem

The most important factor affecting the transient response of a delay line is almost certainly the degree to which the delay time remains constant as a function of frequency. This is another way of saying that the phase response of the network should be a linear function of frequency. Although networks providing constant time delay are reasonably well known in lumped-circuit theory and practice,[1, 2] relatively little has been realized in the design of delay networks using distributed parameters.[3, 4] The principal difficulty in the design of distributed-winding delay lines arises from the presence of high, positive, mutual inductance between the turns of a coil that has a reasonable Q. The mutual inductance between the two representative turns as their axial

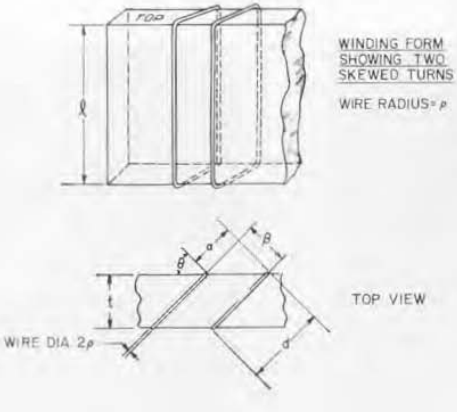

Figure 2. Diagram of two turns on form of rectangular cross section.

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[1] A. H. Turner, "Artificial lines for video distribution and delay," *RCA Review*, vol. X, no. 4, pp. 477–489; December, 1949.

[2] E. L. Ginzton, W. R. Hewlett, J. H. Jasburg, J. D. Noe, "Distributed Amplification," *Proc. IRE*, vol. 36, pp. 956–969; July, 1948.

[3] H. E. Kallman, "Equalized delay lines," *Proc. IRE*, vol. 34, pp. 646–657; September, 1946.

[4] J. P. Blewett and J. H. Rubel, "Video delay lines," *Proc. IRE*, vol. 35, pp. 1580–1584; December, 1947.

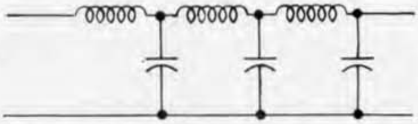

Figure 4. Simplified equivalent circuit of a distributed-parameter delay line, in which each turn is one section of a ladder network.

separation is increased is shown in Figure 3a. Because of the progressive phase shift along the coil of a distributed delay line at a given frequency, it is possible that two turns having a fairly large mutual coupling can carry currents which are not of the same phase. The phase shift thus produces a reduction in the effective inductance of the coil as the frequency is increased.[3,4] The decrease in effective inductance results from the reduction of the in-phase component of the current in a given turn with respect to a reference turn. Thus if a distributed-parameter delay line is constructed with a constant-pitch winding over distributed ground capacitance strips, the time delay, $T_d = \sqrt{LC}$, decreases as the frequency is increased. This problem is obviously not encountered in lumped-parameter networks since there is phase shift only between sections, and mutual inductance between these sections can be adjusted at will. It is instructive to consider the distributed-parameter delay line as a ladder network (see Figure 4) of series L and shunt C elements, each C being the capacitance of the turn to ground and each L being the effective inductance of only one turn, taking into account mutuals to all other turns. Calculation of the effective inductance per turn for a line made with rectangular turns in the distributed winding has been accomplished by considering that each turn is long compared with its width (i.e. it is wound on a thin mandrel). The calculated effective inductance versus phase change per turn of such a constant-pitch distributed-parameter delay line for one particular geometrical arrangement is shown as the curve of a conventional-type winding, $\Theta = 0°$, in Figure 5. Since, in the simple ladder network of Figure 4, the time delay is approximately $T_d = \sqrt{LC}$, it is apparent that satisfactory performance with respect to a constant-time delay characteristic can be obtained with this uncorrected delay line only for low values of delay or phase shift per turn.

Some of the previously proposed modifications of this simple distributed-parameter delay line have produced a form of bridged-T network section by the addition of longitudinal capacitance between turns.[3, 4, 5] However, there are

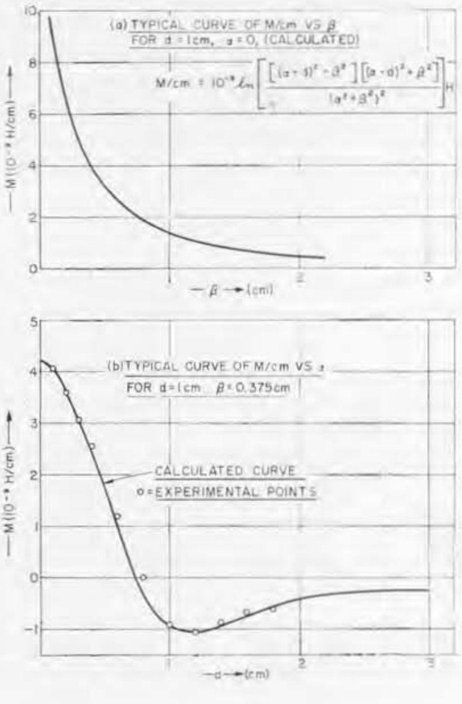

Figure 3. Curves showing variation of mutual inductance, M, between two rectangular turns as (a) their axial separation, β, is varied, and (b) their displacement, d, is varied. (See Figure 2).

limitations and some disadvantages to these modifications. Patch-type compensation causes a large variation of the impedance which is usually within the bandpass of the line. In addition, adequate compensation by means of patches alone cannot be applied easily to low-impedance lines. The use of aluminum paint of high dielectric constant is limited to even higher-impedance lines with relatively low delays per unit length of coil. A direct solution would produce a more nearly constant effective inductance.

Skewed-Winding Delay Equalization

The delay equalization method devised for the new General Radio delay lines uses skewed turns to provide a more nearly constant effective inductance of the distributed winding. As can be seen from Figure 5, skewing the turns of the winding produces an effective inductance which remains nearly constant up to a critical value of phase change per turn. In effect, skewing offers a new means of control over the mutual inductance between turns of a distributed winding delay line. (See Figure 3b). Since the delay $T_d = \sqrt{LC}$ in the ladder network of Figure 4, the delay can thus be made constant without resorting to bridged-T circuit modifications. This simplification allows construction of delay-equalized lines with distributed windings to work at low characteristic impedances without attendant difficulties in getting the large bridging capacitors needed at such low impedances by the other method of equalization. Another advantage of a skewed coil is that a higher Q is obtained for a given inductance and mandrel size.

Several forms of skewed winding have been used experimentally for delay equalization, as shown in Figure 6. For delay lines requiring the use of skewing for equalization of delay, the D-shaped turn on a flat mandrel card appears to be the most satisfactory, since it produces a smooth winding of constant characteristic impedance, which can then be curved to fit the housing of a standard wire-wound potentiometer.

Design Features

The use of silver wire in the winding provides a reliable contact surface for

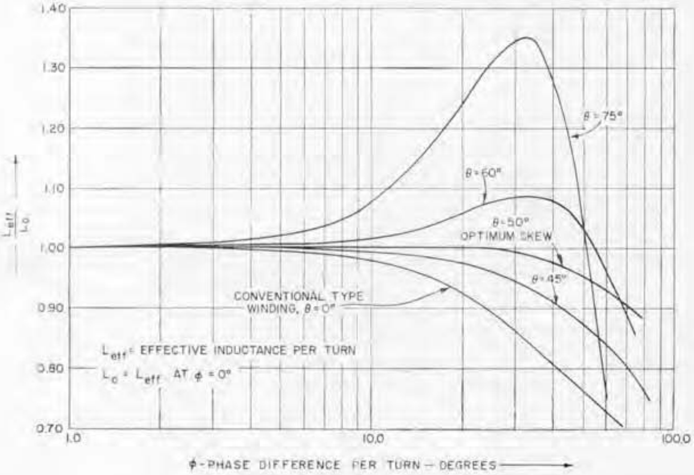

Figure 5. Curves showing effect of various skew angles on the effective inductance per turn versus phase difference per turn.

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[1] W. S. Carley, "Distributed-constant delay lines with characteristic impedances higher than 5000 ohms," *IRE Convention Record*, part 5, Circuit Theory, pp. 646–657; September, 1946.

the moving contact, independent of whether the brush is moved frequently or allowed to stay in one position, as it will be when the line is used as a screwdriver-set unit. The moving contact is made of precious-metal alloy, selected to be compatible with the silver-alloy wire.

Manufacturing processes have been sufficiently refined so that the "baseline ripple," caused by variation of characteristic impedance along the delay line, has been reduced to 5% or less of the signal amplitude. This feature alone is of considerable value in computer and pulse-coding applications. End reflections have been minimized by the use of tapered capacitance elements at the ends of the winding, keeping the impedance relatively constant and resulting in a high degree of freedom from unwanted variations or reflections at points near the ends. Materials used for construction have been selected so that reliable operation is assured even with wide variations of temperature or humidity, and epoxy-type cement is used to insure a permanent bond of all the parts.

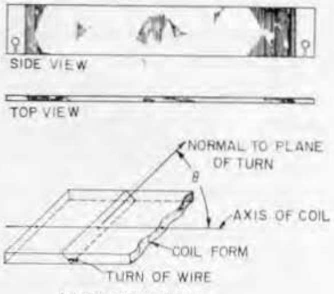
Methods of Application

A common method of obtaining variable delay is shown in Figure 7a. However, this method does not allow matching of the input and output, and in fact, the impedance of the output must be much greater than Z_o. Otherwise, large reflections from the slider are sent back to the source.

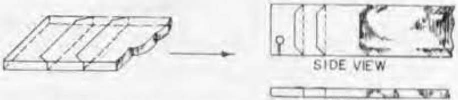
A recommended circuit is shown in Figure 7b where the source is fed into the slider. The source sees one-half the characteristic impedance of the line and maximum power transfer is obtained when the source impedance is $\frac{Z_o}{2}$ and the load impedance Z_o. For equal input and output impedances of $\frac{Z_o}{2}$, a resistor of $\frac{Z_o}{2}$ can be connected in series with the load. This method permits power transfer without the introduction of reflections.

If the load impedance is capacitive, as is the input of a tube, reflections can be minimized by a half section of low-pass filter consisting of the tube input capacitance and an added inductor as shown in Figure 7c.

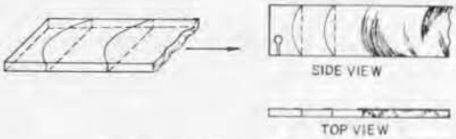
In some cases there may be unwanted voltage loss with the method of Figure 7b. It presents, however, an easy method of obtaining power transfer or of matching without producing reflections.



(a) SKEWED WINDING



(b) EQUIVALENT TRAPEZOIDAL-TURN SKEWED WINDING



(c) EQUIVALENT D-SHAPED-TURN SKEWED WINDING

Figure 6. Diagrams showing arrangement of skewed windings on forms of rectangular cross section; (a) rectangular turns, (b) equivalent trapezoidal turns, (c) equivalent D-shaped turns.

These variable delay lines can also be used as adjustable-length shorted transmission lines by shorting the slider to ground as in Figure 7d. For example, if a positive pulse is fed into the line, a negative pulse will be returned, delayed by twice the delay-time setting.

Variable Delay Line Specification

Most engineers who have used delay lines in one form or another are aware of the difficulty with which the specification of a delay line unit is accurately set down. Part of this difficulty arises from the multiplicity of uses for which delay lines are needed. For example, in some applications it may make little difference whether there is overshoot or ringing in the output signal along with the desired pulse. However, the engineer with these moderate requirements can almost certainly use an equivalent higher-quality delay line which exhibits no ringing or overshoot. In any case, he must know the impedance level, maximum delay time, and attenuation or loss in the line in order to judge its suitability for his application.

The principal difficulties in the specification of variable delay lines arise in the matters of phase distortion, attenuation, and bandwidth. The oscilloscope photographs of Figure 1 contain much of the information necessary to specify these quantities. The response to short pulse excitation indicates pulse stretching or bandwidth, pulse dissymmetry or phase distortion, and pulse amplitude or attenuation.

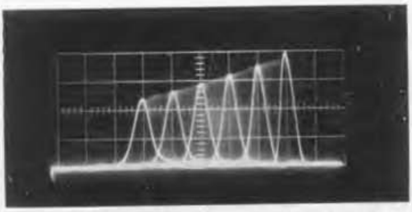


Figure 8. Oscillogram showing pulse shape and pulse amplitude as delay setting is varied. Tektronix 541 Oscilloscope, 53K/54K Pre-Amplifiers; sweep, 0.1 μsec/cm; time scale reads from right to left.

The step response shows rise time or bandwidth, final level or attenuation, and wave shape indicating phase distortion. All scope photographs must have the time scale specified, and the scope should have a much faster rise time than the delay line under test.

A type of oscilloscope photograph which has been found useful for simultaneous determination of the pulse response, impedance uniformity, and end effects is shown in Figure 8. These photographs were obtained by taking a continuous exposure while the slider was slowly moved from minimum to maximum delay. Slightly greater exposure at any point recorded the delayed pulse at that point.

The following information will be supplied for the new General Radio Delay Lines.

1. Impedance, Z_o, and tolerance (at low and intermediate frequencies).
2. D-C resistance.

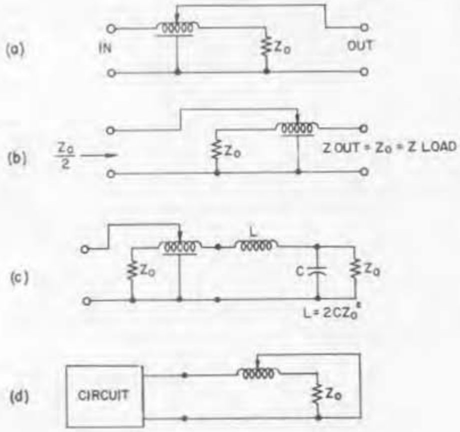


Figure 7. Methods of connection for a variable delay line.

Figure 9. Type 314–S86 Variable Delay Line. Z_0 = 200 ohms, maximum time delay, 0.5 µsec (500 millimicroseconds).

Figure 10. Photograph of skewed-turn delay-line winding opened out to show ground capacitance strips and D-shaped skewed turns.

3. Maximum delay time and tolerance.

4. Departure from constant time delay at several frequencies.

5. Frequency response of amplitude at several frequencies.

6. Rinse time for step input at maximum delay setting.

7. Oscilloscope photographs (not drawings) of waveforms of

a. Short pulse response at maximum delay.

b. Step response at maximum delay.

c. Envelope of response to short pulse over entire delay span.

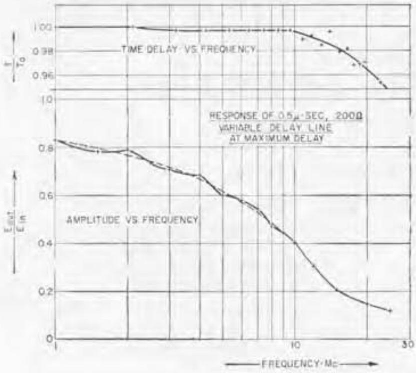
There may be additional quantities which extend or supersede the quantities mentioned above, but until the time when the specification of variable delay line units is further standardized, the information listed above should provide a reasonable basis in choosing a suitable delay line.

Type 314–S86 Variable Delay Line

The Type 314-S86 Variable Delay Line shown in Figure 9 is the type on which much of the development work for these new lines was done. Figure 10 is an exploded view of the winding. This delay line has a characteristic impedance of 200 ohms and a maximum delay of 500 millimicroseconds. The time delay and the amplitude response versus frequency are shown in the curves of Figure 11. The resultant pulse and step responses are shown in the oscillogram of Figure 12.

A primary reason for the development of these new delay lines has been

Figure 11. Time delay and amplitude versus frequency with resistive termination as measured at full delay on 0.5-µsec, 200-ohm variable delay line with skewed winding (See Figure 9).



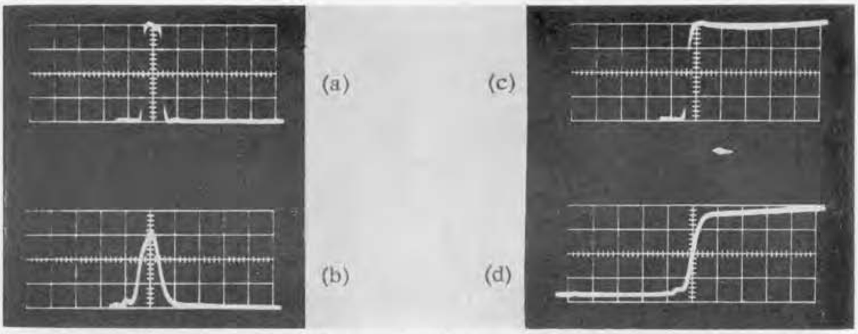


Figure 12. Pulse and step response of 0.5-μsec, 200-ohm variable delay line with skewed winding; (a) pulse input, (b) pulse output at 0.5-μsec delay, (c) step input, (d) step output at 0.5-μsec delay. Scope photos taken on Tektronix 541, 0.1-μsec/cm sweep.

the requirement of quality fixed and variable delay lines in our newer type pulse equipment. Now that manufacturing techniques allow quantity production, these variable delay lines can be offered as a catalog item.

— F. D. Lewis
— Robert M. Frazier

SPECIFICATIONS

Characteristic Impedance: 200 ohms ± 15% at frequencies up to 4.5 Mc.

D-C Resistance: Not over 20 ohms.

Maximum Delay: 0.5 μsec ± 10%
The following quantities refer to maximum delay setting.

Delay vs. Frequency (with respect to delay at 1 Mc): ± 1% up to 10 Mc; ± 2% at 15 Mc; ± 4% at 20 Mc; see Figure 11.

Amplitude Response vs. Frequency: Down 9% (0.8 db) at dc; down 20% (2 db) at 1 Mc; down 30% (3 db) at 6 Mc; down 60% (8 db) at 10 Mc; down 90% (10 db) at 25 Mc; see Figure 11.

Pulse and Step Response: See Figure 12.

Dimensions: Dia., 3 3/16"; depth behind panel, 1½"; shaft dia., 3/8". Knob is furnished.

Net Weight: 6 ounces

Type		*Price*
314-586	**Variable Delay Line**	**$60.00**

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