JERROLD

Technical Newsletter

Published by JERROLD ELECTRONICS CORPORATION, Philadelphia, Pa.
INDUSTRIAL PRODUCTS DIVISION

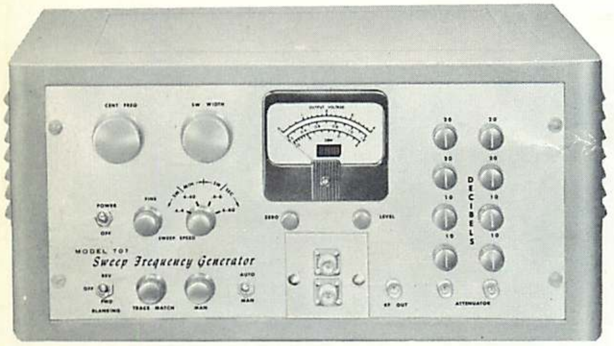
Volume 1, Number 2 August, 1958

Wide Band Impedance Measurement

With a Sweep-Frequency Generator and Delay Line

by KEN SIMONS
Chief Test Equipment Engineer
Jerrold Electronics Corporation

The Sweep-Frequency, Delay Line method of testing was first used in the alignment and test of TV Broadcasting Antennas. Since then it has been widely used in the TV industry where impedance match over a wide band of frequencies was important. This article discusses the basic principles involved, and describes some techniques that allow an increase in measurement accuracy.



MODEL 707
Sweep Frequency Generator

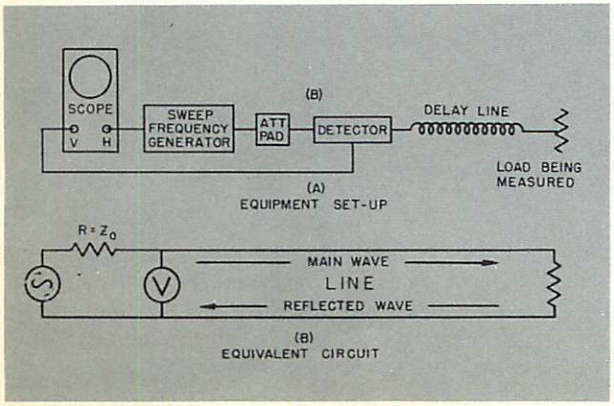


FIGURE 1

Equipment Set-Up

The basic equipment test set-up for wide-band impedance measurements is shown in Fig. 1 (a). An attenuator pad is generally connected between the sweep and the detector to isolate the generator from the varying impedance, and to ensure that the detector is fed from a well-matched source. The detector is needed when the sweep covers a frequency range above the upper response limit of the scope. The high-frequency voltage is rectified, and the detected output, a slowly-varying voltage representing the envelope of the high-frequency input, is applied to the oscilloscope.

The equivalent circuit of the test set-up is shown in Fig. 1 (b). A voltmeter (the detector and scope) measures the voltage at the junction between a matched source and a transmission line with a load on its far end. The voltage at this junction may be considered as being due to the sum of two waves: the *main wave* energy coming out of the sweep and going down the line, and the *reflected wave;* energy which has travelled down the line, been reflected from the load, and come back up the line.

The Delay Line

Terminated Line

With a well-designed sweep, the main-wave is made approximately constant with frequency. When the delay line is terminated in a resistance equal to its characteristic impedance, there is no reflected wave, so the scope shows a constant voltage. Fig. 2 illustrates a typical pattern. On the forward trace the output stays constant as the frequency changes across the sweep band. The reverse trace is "blanked"; the sweep output being keyed to zero to provide a reference line showing where zero output is.

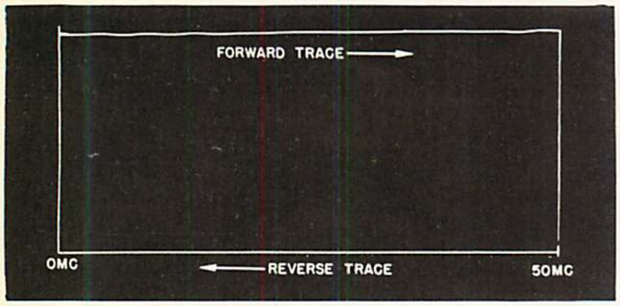


FIGURE 2

Open Circuit Line

When nothing is connected to the end of the line this "open circuit" cannot dissipate, so all the energy striking it is reflected. When the line loss is small, the reflected wave at the detector has essentially the same amplitude as the main wave, and the total voltage there depends only on their phase relation. When they are in phase, they add to produce a voltage twice the "main wave only" condition. When they are 180° out of phase, they cancel to produce zero output. Fig. 3 illustrates the pattern with a generator sweeping 0 to 50 mc, and an open-circuited delay line ½ wavelength long at 50 mc. The reflected wave *at the open circuit* is in phase, at all frequencies, with the main wave. Near zero frequency the effective length of the line is zero so the two waves are in phase and add at the detector, producing a maximum. At 25 mc, the line is ¼ wave-length long; the main wave shifts 90° in phase as it travels down the line to the end; and the reflected wave shifts another 90° on its way back, so the two components are 180° out of phase at the detector, giving a minimum at that frequency. At 50 mc, the reflected wave has travelled a full wavelength (½ wave down, ½ wave back) by the time it gets back to the detector so the components add to a maximum.

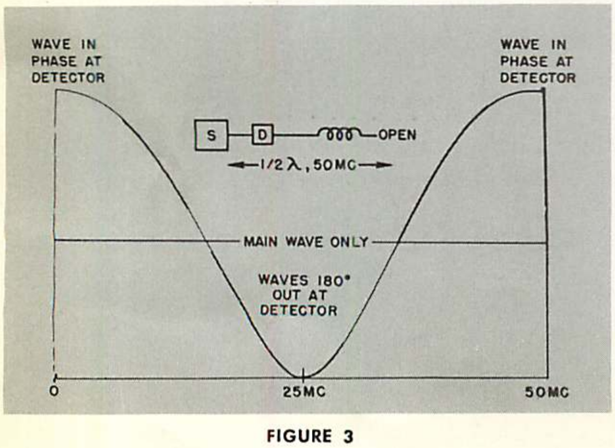


FIGURE 3

Short Circuit Line

Fig. 4 illustrates the pattern obtained by connecting a short circuit across the end of the line. This reverses the phase of the reflected wave so that the two components are 180° out at the short, and produce zero voltage there. At the detector, this produces a minimum at zero frequency (effective line length 0), a maximum at 25 mc., (reflected wave shifted 180° having travelled ½ wavelength extra), and a minimum again at 50 mc.

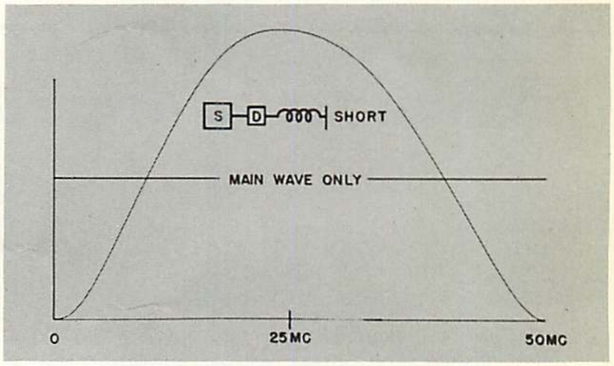


FIGURE 4

Longer Delay Lines

Fig. 5 shows the effect of doubling the length of the line, keeping the sweep-width the same. With an open-circuit (a) there are maxima at 0 frequency (0 line length), 25 mc. (½ wavelength) and 50 mc (1 wavelength) and minima when the line length is ¼ and ¾ wavelength. A short-circuit termination gives the reverse pattern (b).

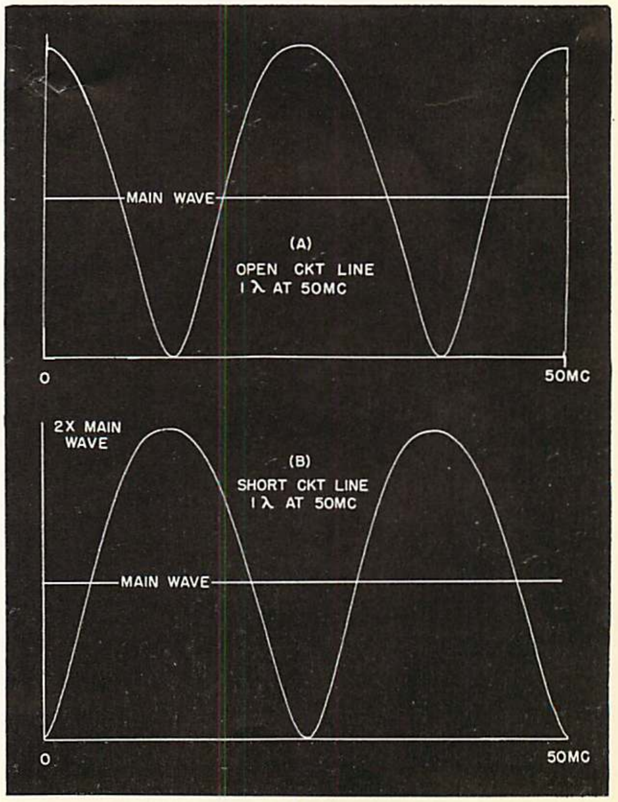


FIGURE 5

It is apparent that increasing the length of the delay line increases the number of ripples occuring in a given sweep-width. Specifically, the frequency change from one maximum (or minimum) to the next is equal to the frequency at which the line is one-half wavelength long. For a spacing of f mc between peaks, the line length in feet is $\frac{492\ d}{f}$ where d is the delay factor, the ratio of the speed with which a wave travels in the particular type cable, to the speed in air. d equals 0.67 for solid polyethylene insulated cables, and approximately 0.8 for polyfoam or other dielectrics with a high proportion of air insulation.

Since more ripples depict more clearly what happens in a given frequency band, in this respect, longer lines are preferred over shorter ones. One factor that limits the length that may be effectively used is the line attenuation. As the length is increased more and more energy is lost in the line, so the reflected signal, as it shows up back at the detector, gets increasingly weaker. Fig. 6 (a) shows the ripple pattern resulting with a short-circuit termination, a sweep from 50 to 100 mc., and a high-grade delay line for 5 mc. between peaks.

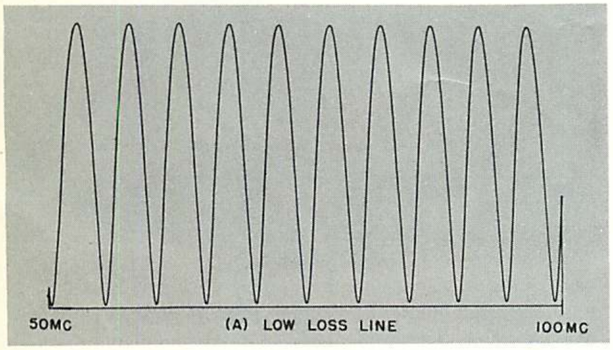


FIGURE 6a

The delay factor for this cable was 0.8, so its length, by the formula, would be $\frac{492 \times 0.8}{5}$ or 79 feet. Due to the greater length of this line, and the higher frequencies involved there is appreciable loss in the line. Although the reflected wave at the shorted end is equal to the main wave (reflection—100%), the main wave is stronger at the detector than it is at the far end, due to attenuation as it travels down the line, and the reflected wave is weaker at the detector than it is at the load, due to attenuation as it travels up the line from the load. This shows up on the ripple pattern in the fact that the minima do not quite go to zero, since the weakened reflected wave does not quite cancel the main wave.

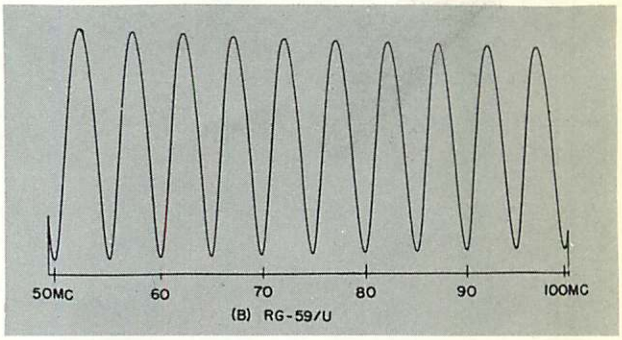
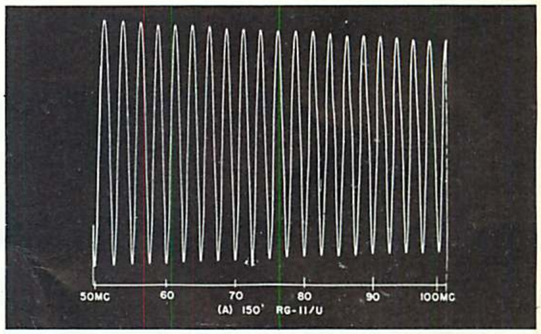


FIGURE 6b

Fig. 6 (b) shows the effect of using a cheaper cable (RG59/U) with higher loss. This line was cut for the same electrical length, but because its delay factor is 0.67, its physical length was shorter, 66 feet. Its greater attenuation shows up in the fact that the minima are still farther from zero. Notice that this effect is more pronounced at the high frequency end of the sweep, where the line loss is higher.

Fig. 7 (a) shows the ripple pattern from approximately 150' of RG11/U cable, shorted at the far end. Notice that the amplitude of the ripple pattern is about the same as that from the 66' piece of 59/U in Fig. 6 (b). The attenuation of RG11/U is about one-half that of RG59/U for a given length; so doubling the length just about cancels the attenuation improvement due to the larger cable. Fig. 7 (b) shows the pattern from about 500' of RG11/U showing the great reduction in ripple height at this length.



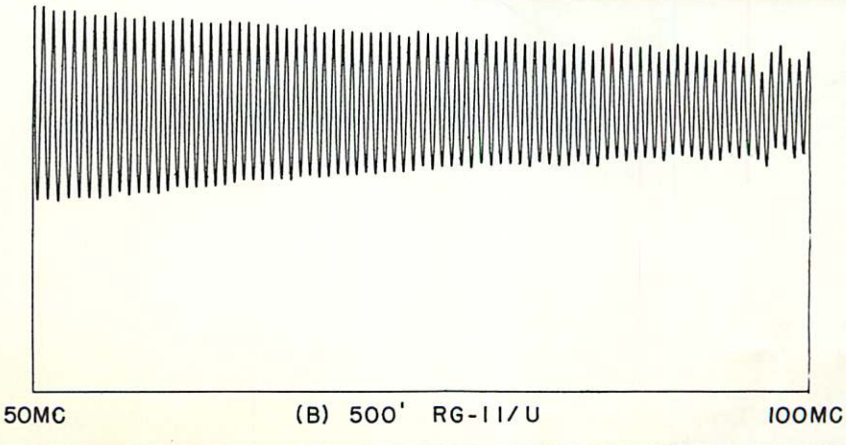


FIGURE 7

Terminations

Various Resistive Terminations

The wave reflected from a purely resistive termination is in phase with the main wave at the load for resistance values higher than Zo, or 180° out of phase for values lower than Zo, and the amplitude of the reflection increases as the resistance differs from Zo.

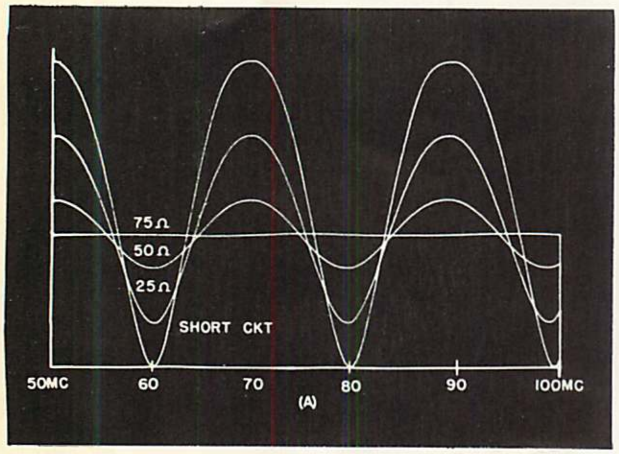


FIGURE 8a

Fig. 8 (a) shows superimposed the ripple patterns obtained with a low-loss 20 mc delay line, a sweep from 50 to 100 mc, and the indicated terminations. Note that all the patterns have minima at the same frequency as that with a shorted end.

> The impedance of a load giving a minimum at the same frequency as a short circuit is resistive and lower in resistance than Zo.

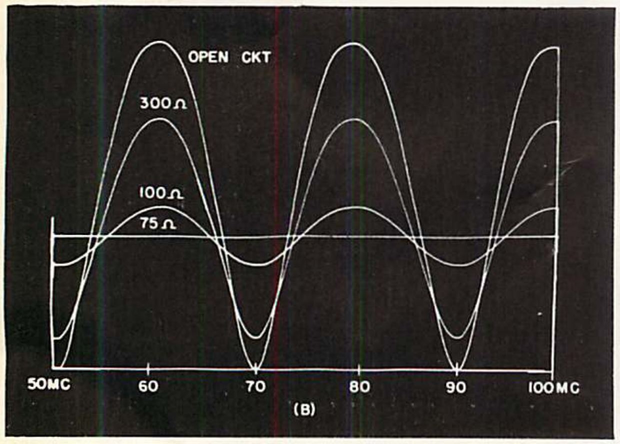


FIGURE 8b

Figure 8 (b) shows the patterns from several resistive terminations higher than Zo. They all have maxima at the "short-minimum" frequencies.

> The impedance of a load giving a maximum at the same frequency as a short-circuit minimum is resistive and higher in resistance than Zo.

Purely Reactive Terminations

A pure reactance does not dissipate energy, so the wave is reflected from a purely reactive termination at full amplitude. Its phase is shifted depending on the magnitude of the reactance relative to Zo. Thus the ripple pattern obtained with purely reactive terminations has the same amplitude as with an open or short circuit, but the minima and maxima are shifted in frequency. Fig. 9 (a) shows the patterns obtained with two sizes of capacitors compared with open and short circuit patterns.

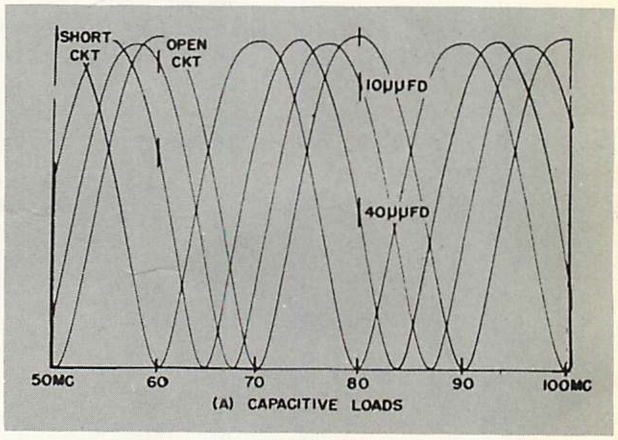


FIGURE 9a

The ripple pattern resulting from a capacitive termination has minima falling higher in frequency than those due to a short circuit, and lower than those due to an open circuit. This may be stated another way:

> If we mark the frequencies of short circuit minima (see marks on Fig. 9a) the marks will fall on down slopes with a capacitive load.

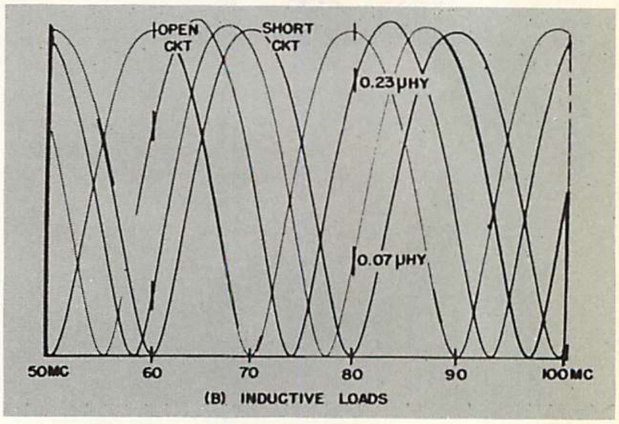


FIGURE 9b

Fig. 9 (b) compares the ripple patterns for two sizes of purely inductive terminations with those from an open and a short circuit.

> The ripple pattern from an inductive termination has minima falling above those from an open circuit, and below those from a short circuit. If we mark the frequencies of short circuit minima, the marks fall on upslopes for inductive terminations.

Complex Terminations; Impedance Changes with Frequency

When a termination has both dissipation (resistance) and reactance the reflected wave is reduced in amplitude, and shifted in phase relative to the main wave. Correspondingly, the ripple pattern has a lower amplitude, and minima shifted in position compared with a short or open circuit. Fig. 10 (a) illustrates the ripple pattern obtained with a low-loss 5 mc delay line and a series RC termination. At higher frequencies, where the reactance is lower, the termination approaches a matched condition, and the ripple has lower amplitude. The nature of the termination can be seen more clearly if the ripple pattern is compared with that obtained with a short circuit, and that obtained with a matching resistance. Fig 10 (b) shows the three patterns superimposed. By observing the fact that down-slopes occur at shorted-minimum frequencies, and the ripple gets smaller at high frequencies, we could conclude that the load had the characteristics of a series RC circuit.

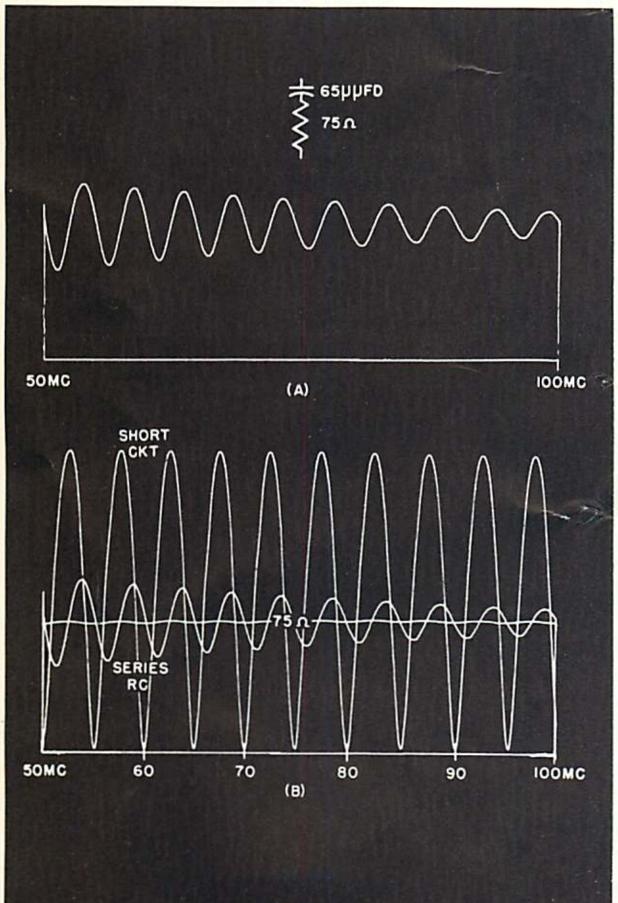


FIGURE 10

Fig. 11 (a) shows the ripple pattern with a 20 mc line and a series resonant circuit. Fig. 11 (b) shows the same pattern superimposed on a short circuit pattern and one from a matched resistor. By observing that its impedance is capacitive below the resonant frequency (down-slope at short-circuit minimum frequencies), matched at resonance (low ripple amplitude near 75 mc), and inductive above resonance (up-slope of shorted-minimum) we could deduce that it was a series RLC circuit with R equal to Zo.

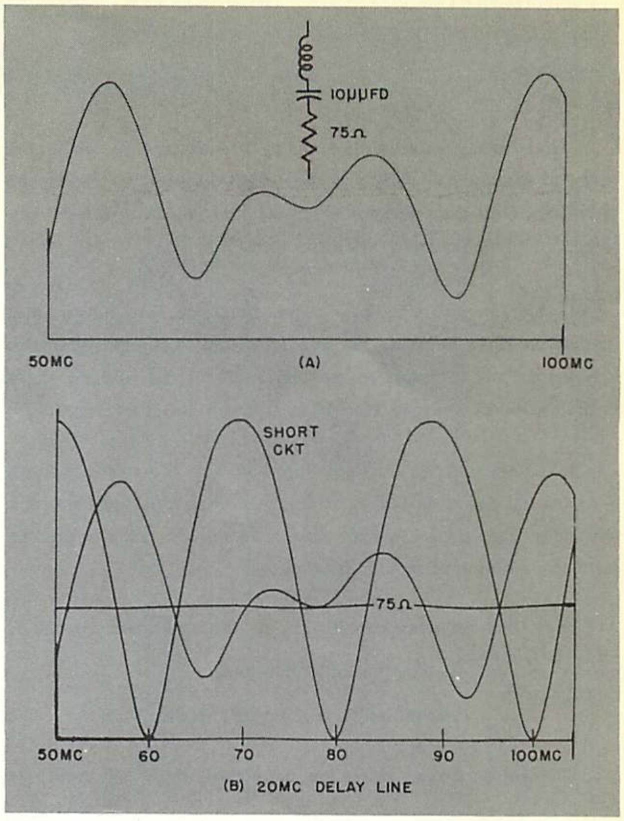
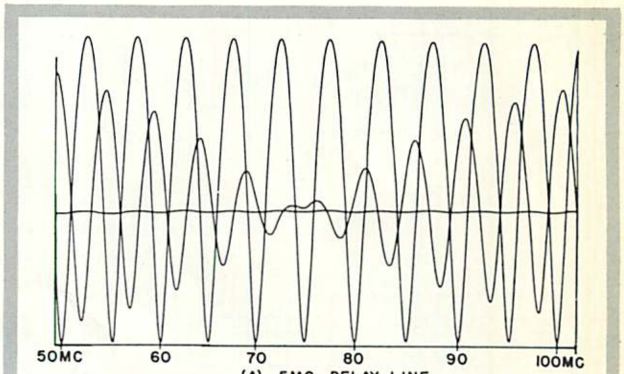
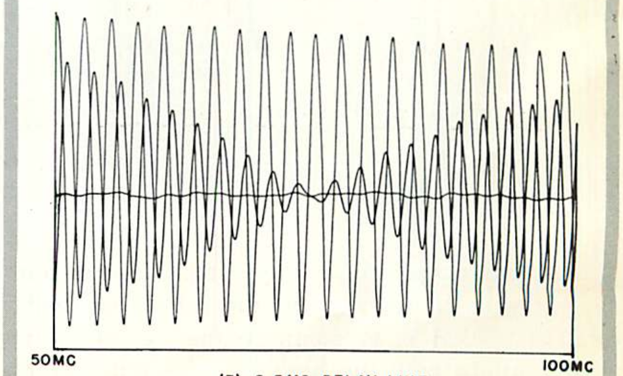


FIGURE 11

Fig 12 (a) and (b) show the ripple patterns obtained under the same conditions as Fig. 11 (b) but with 5 mc and 2.5 mc delay lines respectively. They show how increased length in the delay line depicts the impedance characteristic in more detail.



(A) 5MC DELAY LINE



(B) 2.5MC DELAY LINE

FIGURE 12

Determining Reflection Coefficient and VSWR

There is a temptation, in using the delay-line technique, to assume that the VSWR of the load is found by taking the ratio of minimum to maximum of the ripple pattern displayed on the scope. Two factors, the loss of the delay line and the non-linearity of the detector, make this procedure quite inaccurate. A more accurate procedure that eliminates the effect of the line loss and minimizes detector non-linearity is to compare the amplitude of the ripple pattern from the unknown with that from a short- or open-circuit.

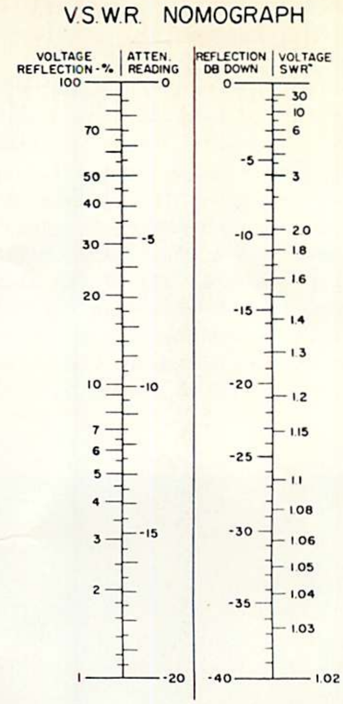
Let A be the peak-to-peak amplitude of the ripple pattern obtained at the frequency of interest with the line shorted. Let B be the peak-to-peak amplitude of the ripple pattern from the unknown at this frequency.

Then the reflection coefficient of the unknown (ratio of main wave to reflected wave): K equals $\frac{B}{A}$

Percent reflection equals 100K

The *Return Loss* (reflection coefficient as a DB ratio) is $20 \log_{10} \frac{1}{K}$

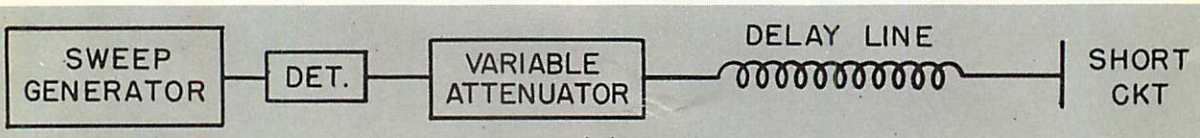
The VSWR (ratio of max voltage at load to min. voltage is $\frac{1+K}{1-K}$ These various ways of expressing the degree of mismatch are conveniently related by the nomogram shown in Fig. 13.



NOTE:

$SWR = \frac{E\ MAX}{E\ MIN.}$ AND $\%\ REFLECTION = \frac{(SWR)-1}{(SWR)+1} \times 100$

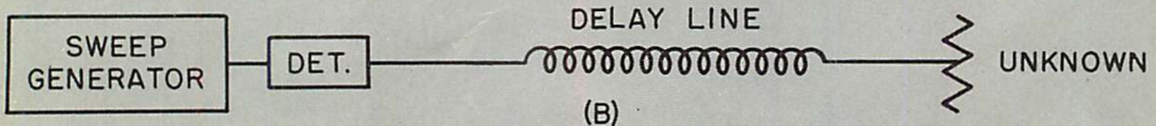
FIGURE 13



(A)

FOR THIS SET-UP

Reflected wave at detector is equal to main wave decreased by 2 X line loss and by 2 X attenuator setting.



(B)

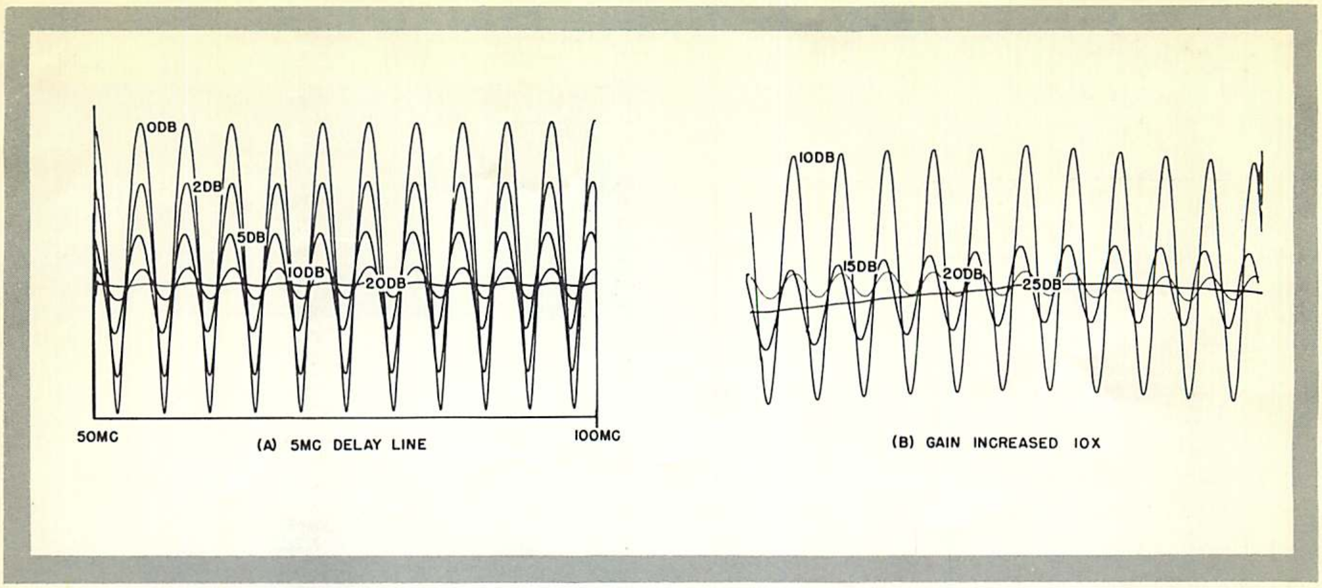
FOR THIS SET-UP

Reflected wave at detector is equal to main wave decreased by 2 X line loss and by the return loss (Reflection Coeff) of unknown.

If attenuator in (a) is set for same ripple height as from unknown in (b)
Return loss of unknown = 2 X Att Setting in DB

FIGURE 14

A more accurate, and generally more convenient way of determining the reflection coefficient of a load is to compare the height of its ripple pattern with the height of the pattern obtained with a short at the far end of the line, and a variable attenuator inserted between the line and the detector. Fig 14 illustrates the calibration set-up. By putting the attenuator at the detector end of the line the ripple height is determined primarily by its attenuation, and its impedance match is less important than if it were connected at the load end of the delay line.

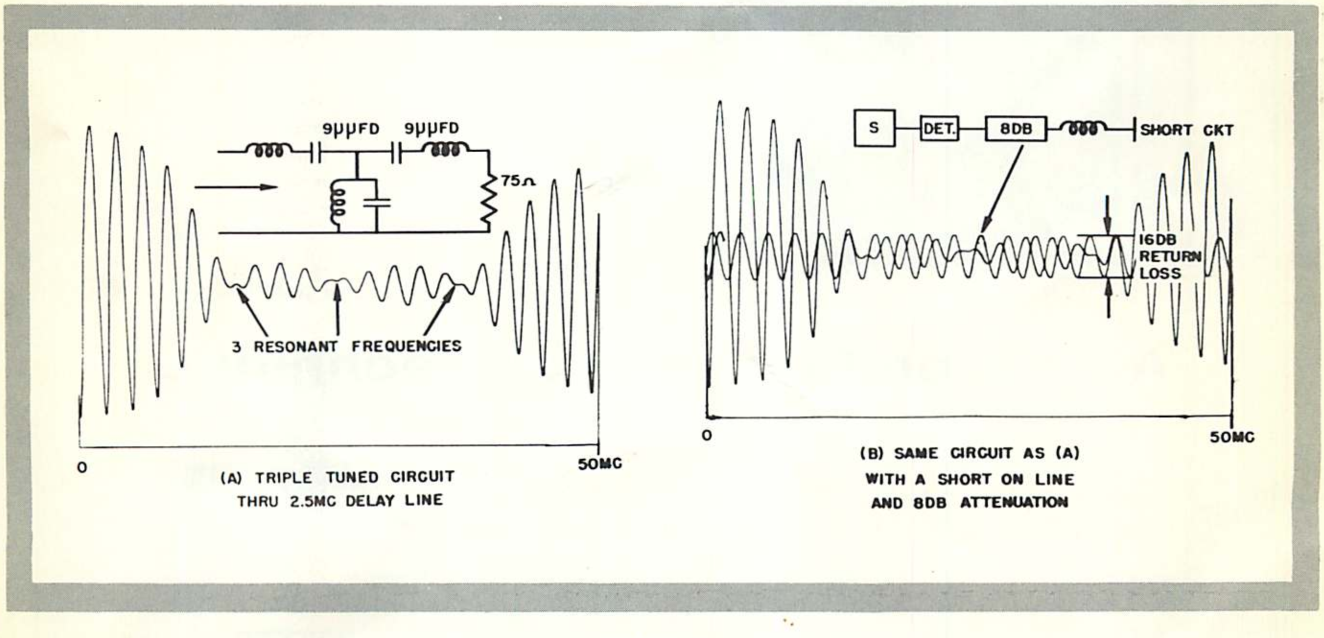


(A) 5MC DELAY LINE

(B) GAIN INCREASED 10X

FIGURE 15

Fig. 15 illustrates the ripple patterns obtained at various settings of an attenuator connected in this way. Note that the ripple height with, for example, 5 db set on the attenuator, is what would be seen from a load having a return loss of twice this many db (e. g. 10 db). Fig. 15 (b) was made by increasing the vertical gain 10X compared with (a). Note that the ripple corresponding to a return loss of 40 db (VSWR 1.02) is readily seen. Also, note the irregularities in the way these traces match up. These are due to very small errors in the impedance match and delay of the attenuator used.



(A) TRIPLE TUNED CIRCUIT THRU 2.5MC DELAY LINE

(B) SAME CIRCUIT AS (A) WITH A SHORT ON LINE AND 8DB ATTENUATION

FIGURE 16

Fig. 16 illustrates how the technique is used in determining return loss. A triple-tuned band-pass filter was connected to the end of a 2.5 mc delay line, giving the ripple pattern of Fig. 16 (a). Note the three frequencies of best match. To determine the maximum reflection within the pass band, the ripple from a shorted line through a variable attenuator was set to the same height as the maximum ripple in the pass band. The attenuator read 8 db. indicating a maximum return loss for this filter of 16 db. The two patterns are shown superimposed in Fig. 16 (b).

Irregularities in the Delay Line

With reasonable sweep output level and scope gain, it is not difficult to see ripples corresponding to 40 or even 50 db return loss. It is not generally possible to make measurements with this much accuracy. The limiting factor is not gain, but the uniformity of the delay time. Many commercial coaxial cables have a degree of nonuniformity that results in appreciable reflections from within the cable, even when terminated with the best possible load. A poor cable may have reflections with a return loss of as little as 20 db. Most cables run at or above 30 db., and only an exceptionally uniform cable has internal reflections more than 40 db down. To illustrate the extremes that may be encountered several traces were made. Fig. 17 (a) shows the ripple pattern of a 5 mc delay line of exceptional uniformity terminated in a load that closely matches its impedance. It was possible to see variations in the pattern only by increasing the vertical gain 10X (Fig. 17b). Comparing the ripple pattern with the calibration pattern corresponding to 40 db return loss, it can be seen that the combined return loss of cable and termination is decidedly better than 40 db over the whole frequency range of the sweep. For contrast, Fig. 17 (c) shows the trace with a very poor piece of cable. Even with the best termination possible, its variation is more than 10X greater than the other cable. (compare with 17a).

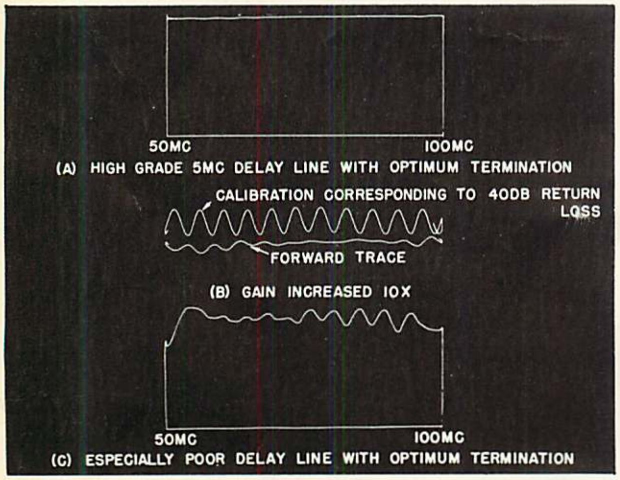
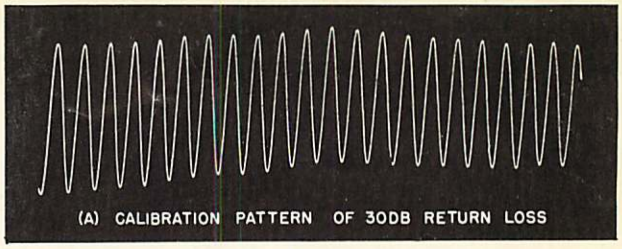
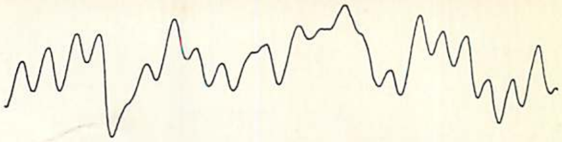


FIGURE 17





(B) OPTIMUM TERMINATION

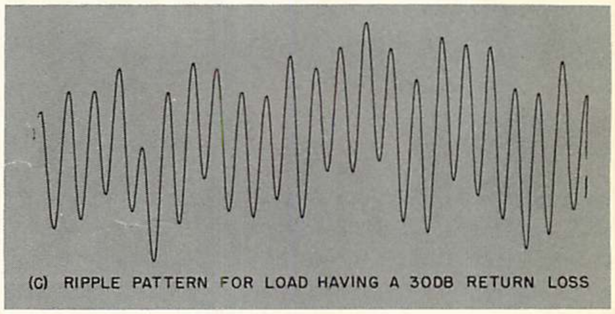


FIGURE 18

Fig. 18 is an illustration of the way in which irregularities in the delay line can make accurate measurement difficult. (a) shows the ripple pattern amplitude under a calibration condition corresponding to 30 db return loss (high vertical gain was used). (b) shows the pattern with termination adjusted for minimum ripple. This line, a 150' length of RG11/U, has internal reflections a little more than 30 db down. (c) shows the pattern resulting when a load having a return loss of 30 db was connected to the end of this line. It can be seen that the line irregularities prevent accurate display of the load characteristics. A further hazard is that the internal reflections probably indicate a considerable variation in characteristic impedance of one section of the cable as compared with another. Thus, the impedance which will match the far end depends on just where the cable is cut.

A Note on Comparison Technique

The patterns illustrating this article were recorded with a Moseley X-Y recorder, using a Jerrold Model 707 Precision Sweep Generator, which has sweep speeds adaptable to use either with a recorder or a normal oscilloscope. Where patterns are shown superimposed, they were made by simply changing the load connections without touching the sweep settings and recording the second trace on top of the first. This is, of course, not possible with a scope, but the same convenience of simultaneous presentation for calibration can be obtained by using a Jerrold Model FD-30 Coaxial Switch. For Delay Line work, it is connected as shown in Fig. 19, superimposing a calibration pattern from a second delay line on the pattern of the load being adjusted or measured.

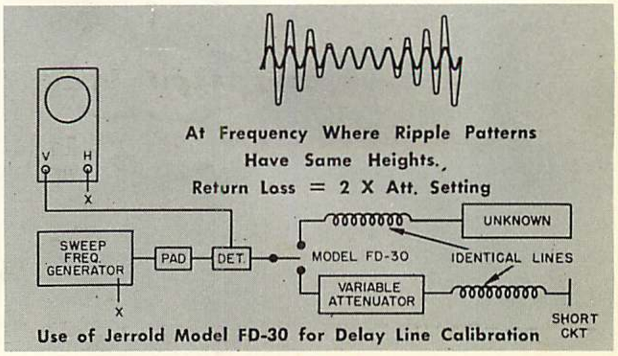


FIGURE 19

NOTE — Additional copies of this paper and engineering assistance on the application of Measurements By Comparison may be obtained by contacting the Industrial Products Division, Jerrold Electronics Corporation, 15th and Lehigh, Philadelphia 32, Pa. Phone: BAldwin 6-3456 — Ext. 211.

EDITORIAL STAFF: MANAGING EDITOR - C. C. Cooley, Jr. — TECHNICAL COPY EDITOR - A. Kirkaldy, Jr.
ART DIRECTOR — R. S. Reisner, Jr.