# Good Practice in Slotted Line Measurements

A REVIEW of the literature will disclose that much has been written on the subject of proper techniques for making measurements with slotted lines, but such information is generally interspersed among other information. With the increasing amount of work going on at UHF and SHF frequencies, many engineers find themselves with a need for making slotted line measurements for the first time. Others have only occasional need for such measurements. In either case the engineer must do considerable research to obtain a coherent overall picture of good practice and of the equipment available for the particular measurements to be made. As a result of this situation, instances occur rather frequently where erroneous results are obtained because of oversight of some



Fig. 1. *Typical set-up for making slotted-line measurements using square-wave-modulated signal generator, slotted section, and standing-wave indicator.*

characteristic of the various devices used in slotted line work.

A generalized set-up for measurements with a slotted line section is shown in Fig. 1. A signal source, usually a signal generator or internal-cavity reflex klystron at UHF-SHF frequencies, feeds through a slotted section to the load whose characteristics are to be measured. The signal source is commonly amplitude-modulated in order to simplify the design of the associated measuring equipment. The fields in the line are sampled by means of a probe which protrudes into the slotted section. The sampling probe may connect to a detector which in turn connects to an indicating device such as a high-gain audio voltmeter calibrated in standing-wave ratio; or the probe may connect directly to a receiver in which case modulation of the signal source can be omitted.

In this generalized set-up, some six different devices are employed and it is possible that each of these devices will introduce effects that contribute to errors. Fortunately, it is possible to reduce most of these effects to the point where they have negligible influence. In fact, the substance of good practice when making measurements with slotted lines is insuring that these effects are made negligible. The following discussion of good practice pertains in general to measurements made with either coaxial or waveguide slotted lines; special mention is made when only one type of system is involved.
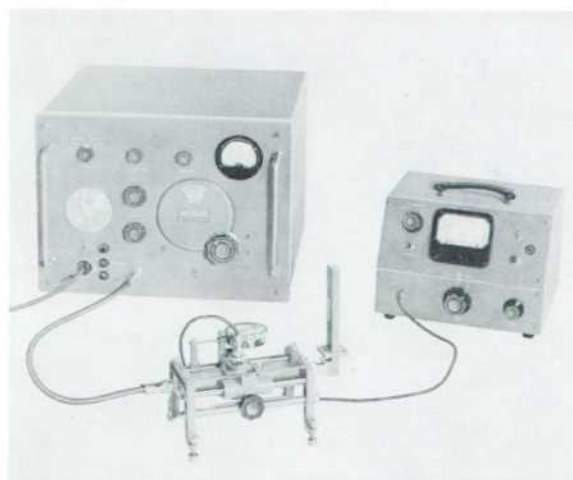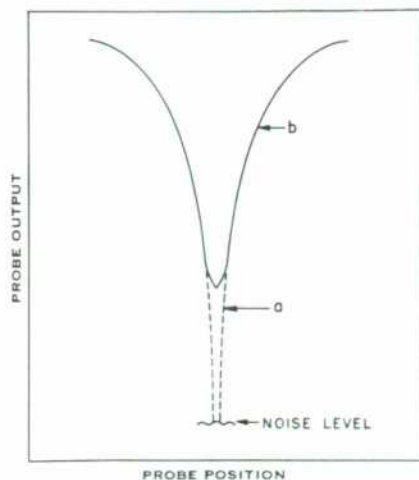
Fig. 2. *Plot of field pattern obtained on high standing-wave ratio when signal source is (a) free of f-m and (b) when signal source has moderate f-m.*

## SIGNAL SOURCES

Signal sources can introduce at least three undesirable characteristics that will affect slotted line measurements. These include: presence of r-f harmonics, presence of f-m and presence of spurious signals.

Instances are common where the presence of r-f harmonics has led to very serious errors in VSWR measurements. Such harmonics are usually present to an excessive degree only in signal sources that have coaxial outputs. Coaxial pick-ups of a broad-band type will often pass harmonic frequencies with greater efficiency than the fundamental. In waveguide systems, signal sources such as internal cavity klystrons have a more or less fixed coupling and, in addition, do not have pick-ups extending into the tuned cavity to cause perturbations of the cavity fields. Consequently, the harmonic problem is generally limited to coaxial systems.

Harmonics become especially troublesome when the reflection coefficient of a load at a harmonic frequency is much larger than at the fundamental frequency—a common condition. When the harmonic content of the signal source is high, the large reflection coefficient of the load at the harmonic frequency can cause the harmonic standing-wave fields to be of the same order of magnitude as the fields at the fundamental frequency. Thus, a device having VSWR of 2.0 at the fundamental frequency will often have a VSWR of 20 or more at the second harmonic frequency. If such a device is driven from a signal source having, say, 15% second harmonic, the peaks or maxima of the standing waves of second harmonic will be about one-fourth the amplitude of the maxima at the fundamental frequency. Since most slotted line probes must be experimentally tuned to the r-f frequency, it becomes easy to mis-tune the probe to the second harmonic instead of the fundamental, in which case a VSWR of 20 or more instead of 2.0 would be measured.

While it is easy to check that the probe is properly tuned by measuring the separation of minima, other errors can result from harmonics since probes can couple significant energy into the detector at harmonic frequencies as well as at the fundamental. This is particularly true of untuned probes and is also prevalent in tuned probes of the distributed type. Under such conditions, the reading obtained will be a combination of the fundamental and harmonic standing-wave patterns.

When the signal source is a signal generator, information is usually available from the designer concerning the harmonic content in the generator's output. In other cases or whenever significant harmonics are present or suspected, suitable low-pass filters should be inserted between the source and the remaining equipment to reduce harmonics to a negligible value.

### F-M

A typical standing-wave pattern resulting from the presence of excessive f-m in the signal source is shown in Fig. 2. It can be seen that the minimum or trough, instead of falling to its natural value, appears to have a
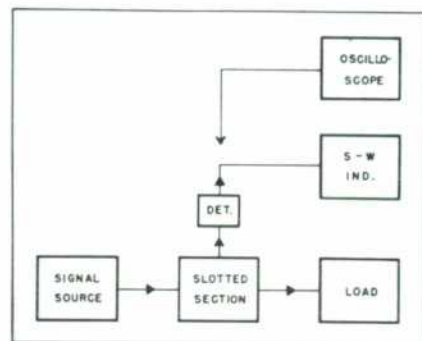


Fig. 3. *Recommended set-up for standing-wave measurements includes oscilloscope to observe detector output.*
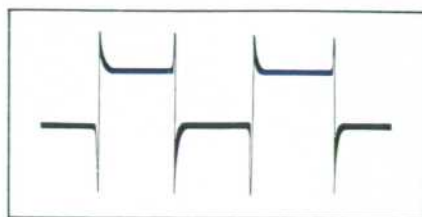
much larger value. With some types of f-m, the trough can consist of two or more different minima. Other portions of the pattern can also exhibit irregularities when excessive f-m is present. Under circumstances such as these a casual measurement of VSWR can easily lead to significant errors.

F-m can occur in any modulated oscillator and generally increases with the degree of a-m modulation. In klystron type signal sources, f-m usually occurs because of poor filtering of the klystron power supply. Occasionally, however, an attempt is made to sine-wave modulate a klystron without consideration of the fact that such modulation results in f-m. Presence of f-m can be detected by investigating the depth of a minimum when the load is a short as in Fig. 2.
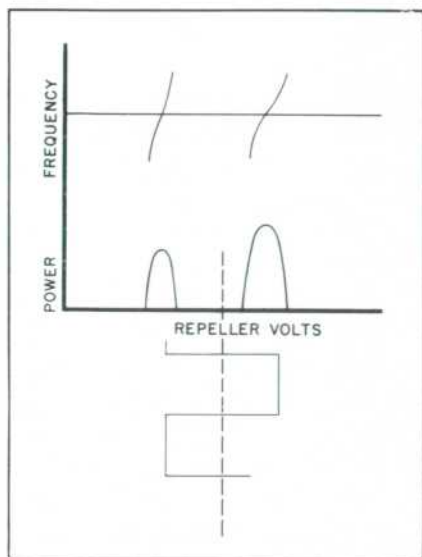
### SPURIOUS SIGNALS

Referring to the generalized set-up shown in Fig. 3, it will be seen that an oscilloscope is included as part of the set-up. Use of an oscilloscope does not seem to be common practice, but such an arrangement is regarded as essential when square-waving klystrons other than those for which signal generator modulation circuitry is provided.

Ordinarily, in tuning up a klystron, it is customary to adjust the repeller voltage for maximum power output at the desired frequency. If square-wave modulation is then added without regard to the operat-

(a)



(b)

Fig. 4. (a) *Drawing of detector output observed when modulating under condition shown in (b);*

(b) *Typical modulation condition obtained when changing repeller voltage without use of oscilloscope.*

ing voltages, the repeller voltage excursions will be incorrect. On square-wave peaks the repeller voltage will not stabilize at the maximum power output point but will be swung between a point which may or may not be in the desired mode and a point that can lie in an undesired mode. When this occurs, two frequencies will be present in the output of the klystron with results similar to those described above under "F-M."

An oscillogram illustrating the detected output of a signal source that has been incorrectly modulated is shown in Fig. 4. Here, two closely-spaced frequencies are present and the resultant standing-wave pattern obtained with this signal is shown in Fig. 5.

It should also be noted that it is possible to obtain a two-frequency output when the square-wave voltage passes through an unsuppressed mode during its leading or trailing edge. Such a condition is more likely to occur at the trailing edge of the square-wave because of the relatively slow decay of charged capacities in the circuit.

Precautions should be taken whenever square-wave modulation is applied to the repeller through a capacitor. This will usually apply whenever using a general-purpose klystron supply. When square-waving, it is necessary to adjust the repeller voltage and the modulating voltage so that modulating peaks will lie in the desired repeller mode while the modulating troughs will not lie in any mode that will permit the tube to oscillate. It is also desirable that the rising and falling portions of the modulating voltage not pass through undesired modes.

**PROBE PENETRATION**

A general rule in slotted line work is that the penetration of the sampling probe into the line should be held to a minimum. However, this rule is so generally disregarded that it is one of the major sources of errors.

Since the sampling probe must extract some power from the line in order to supply the detector and indicating device, it is to be expected that the probe can have an effect on the fields within the line. This effect usually becomes greater as probe penetration is increased. Probe penetration and its effects are described in the literature[1] where it is shown that the probe can be considered as an admittance shunting the line. In practical work this admittance is kept small by coupling as loosely as possible (small penetration) and by using a high-sensitivity detector in conjunction with a signal source

[1]C. G. Montgomery, "Technique of Microwave measurements," Vol. II, Rad. Lab. Series, 1947, pp. 483-488.

having a power output in the order of one milliwatt or more.

If the coupling between the probe and line is not small, the shunt admittance introduced by the probe will cause the measured VSWR to be lower than the true VSWR and will shift both the maxima and minima from their natural positions. The effect of probe conductance on the measured VSWR is shown in Fig. 6.

An exception to the minimum-penetration rule occurs when it is desired to examine in detail a minimum point in a standing-wave of high ratio. For this work a greater probe penetration can be tolerated than otherwise, because the minimum corresponds to a low-impedance point in the line. However, the minimum should be definitely small (high VSWR) before tolerating substantial probe penetration.

**DETECTORS**

No discussion of slotted line measurements would be complete without mention of the precautions to be observed concerning crystal and platinum-wire detector elements. However, the limitations of these devices are well known and will be mentioned only briefly. Both crystals and platinum-wire bolometers exhibit a departure from the ideal square-law response for which standing-wave indicators are calibrated. For crystals this departure tends to occur when the r-f power level exceeds a few microwatts; with barretters a somewhat higher power level can be tolerated. However, the
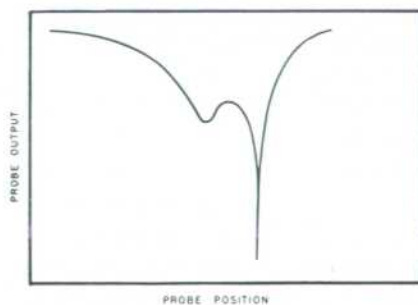


Fig. 5. *A typical field pattern obtained on high VSWR owing to spurious frequency in signal source.*
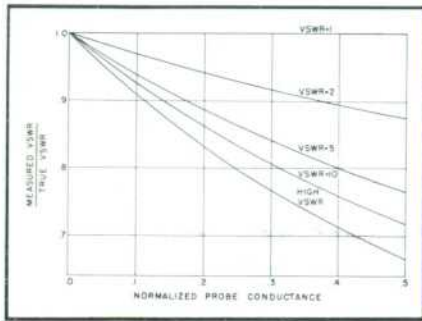
Fig. 6. *Effect of probe penetration on measured VSWR.*

sensitivity of crystals is considerably better than with bolometers so that crystals are widely used as detectors for VSWR measurements.

The characteristic of either a crystal or bolometer is easily checked with slotted line equipment by increasing the power level in the line in known steps and noting the detector response on the standing-wave indicator. Any new crystal being used for the first time should be thus checked, as there is often a significant variation between one crystal and another.

When the detector element is non-square law and yet must be used, it is possible to make standing-wave measurements that do not depend upon the uniformity of response of the detector. Such a measurement involves the use of a signal source with a calibrated attenuator. For best accuracy, it is desirable that the attenuator be of the piston type in which the attenuation follows a natural law determined by physical dimensions. Accurate knowledge of the attenuator dimensions allows the attenuator to be calibrated with a high order of precision. Such attenuators are used in most high-frequency signal generators.

In measuring VSWR with the attenuator, the probe coupling is adjusted at a minimum in the standing-wave pattern to give a suitable reading on the indicator. This should be done while the signal generator or attenuator is set so that the output is a few db less than maximum generator output. The sampling probe should then be moved to a voltage maximum and the output of the signal source reduced by increasing the attenuation until the same reading as before is obtained on the standing-wave indicator. The standing-wave ratio (in db) is then equal to the difference in the readings at the two settings of the attenuator. This method eliminates errors caused by an unknown response characteristic of the detector element, because the element is operated at the same level for both readings.

The most sensitive detector is a good receiver with which can be obtained a gain in sensitivity of several hundred times over that with a crystal. In standing-wave measurements, the receiver replaces both the bolometer element and the standing-wave indicator. Receivers can be used either with modulated or c-w signal sources, depending upon the particular receiver and its output meter.

## HIGH VSWR's

The straightforward measurement of VSWR with conventional methods is generally applicable when measuring nominal VSWR's up to the range of 10-12, but at higher VSWR's special considerations are desirable.

When the VSWR is high, the coupling of the probe must be high if a reading is to be obtained at the minimum. This requirement may result in a deformation of the pattern when a maximum is measured—with consequent error in the readings, as described before. In addition to the error caused by probe coupling, there is danger of the error caused by a change in detector characteristic as the r-f level changes.

Fortunately, there is available for measuring high VSWR's a method that is accurate within approximately 1% down to the region where conventional methods can be used. This method is the twice-minimum-power method and is predicated on the approximation of a high-ratio power standing-wave pattern to a parabola in the vicinity of a minimum.

In the twice-minimum method, it is only necessary to establish the electrical distance between the power points that are twice the amplitude of the minimum. The VSWR can then be obtained by substituting this electrical distance into the expression

$$VSWR = \lambda_g/\pi \, (d_1 - d_2)$$

where $\lambda_g$ is the guided wavelength in cm and $d_1$ and $d_2$ are the locations of the two twice-minimum points, also in cm.

It should be noted that the value referred to in this method is the twice-*power* value. Therefore, if a linear voltage indicator is used with a square-law detector, the voltage indication of the twice-power points will be twice that of the minimum. If a standing-wave indicator calibrated for use with a square-law detector is used or if a linear receiver is used, the ratio of the two readings will be 1.4:1 voltage-wise or 3 db power-wise.

## LOW VSWR's

The fact that the sampling probe penetrates into the slotted section gives rise to reflections from the probe itself. Reflections from the probe travel back toward the generator, and what happens there depends upon the match between the generator and the line. If the generator is mis-matched, these reflections are again re-reflected, this time toward the load. When the probe is moved under these conditions, the phase of the reflections is changed, leading to errors. Since the reflection from the generator is a second-order effect, it only becomes important when measuring low VSWR's in the order of 2 or less, in which case it is desirable to achieve a moderately good match between generator and load. Probe reflections, of course, should be kept as low as possible by minimizing probe penetration.

—*W. B. Wholey*

(To be concluded in next month's issue.)

# Good Practice in Slotted Line Measurements

## *(Conclusion)*

### LOW VSWR's (Continued)

Accurate measurement of the position of the minimum, when the VSWR is low, becomes difficult because of the broadness of the minimum. When the precise location of the minimum is desired, it is helpful to establish points on each side of the minimum that have the same value. By averaging the location of these points, the minimum can be located with greater accuracy than with a direct measurement. The locations of equal-amplitude points are more easily established because of their higher slope.

### MEASUREMENTS

The two types of quantities that are actually measured with the slotted line are the voltage standing-wave ratio and the physical location of minima. This information permits the magnitude and phase of the load to be calculated or to be plotted on a transmission-line calculator.

To obtain the impedance of the load, the VSWR can first be measured. Then, the distance (in cm) between two adjacent minima can be determined. Most slotted lines are equipped with an accurate scale and indicator for this purpose. This measurement will give the length in the line or waveguide of a half wavelength.

Next, the location of a convenient minimum should be measured accurately, although this will have more or less been done in the preceding measurement. Then, the load should be shorted and the amount of shift in the location of the minimum should be measured with the scale.

Next, the electrical length of the shift in the minimum can be calculated from the expression

$$\pm L = \frac{\text{(shift in cm)}}{\text{(half-wavelength in cm)}} \times 180 \text{ degrees}$$

If the minimum is shifted toward the load when the load is shorted, L should be assigned a $+$ value; if toward the generator, L should be assigned a $-$ value.

The impedance of the load can then be calculated from the expression

$$Z_1 = Z_0 \left( \frac{1 - j\,(\text{VSWR})\tan L}{\text{VSWR} - j\tan L} \right)$$

These calculations are based upon the assumption that no losses occur in the transmission system. For laboratory set-ups where the line lengths are short, this assumption is customary. It is also assumed that the $Z_0$ of the lines is entirely resistive. Some rules-of-thumb that are helpful in making slotted-line measurements are:
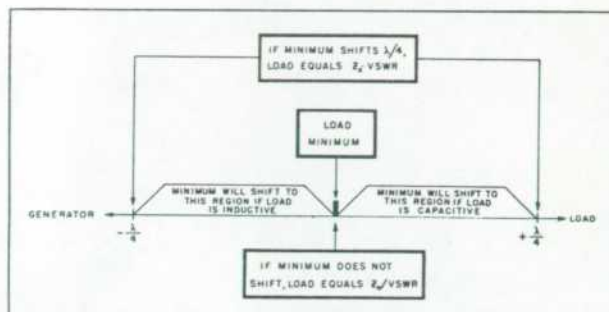


Figure 7. *Diagram illustrating shift in minimum when shorting various loads.*

(1) The shift in the minimum when the load is shorted is never more than $\pm$ one-quarter wavelength.

(2) If shorting the load causes the minimum to move toward the load, the load has a capacitive component.

(3) If shorting the load causes the minimum to shift toward the generator, the load has an inductive component.

(4) If shorting the load does not cause the minimum to move, the load is completely resistive and has a value $Z_0/\text{VSWR}$.

(5) If shorting the load causes the minimum to shift exactly one-quarter wavelength, the load is completely resistive and has a value $Z_0 \cdot \text{VSWR}$.

(6) When the load is shorted, the minimum will always be a multiple of a half-wavelength from the load.

—*W. B. Wholey*