A New High-Precision Method for the Measurement of the VSWR of Coaxial Connectors*

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Summary—**A substitution method of measuring the very small reflections due to a pair of precision coaxial connectors has been developed. The connectors under test are mounted on a section of precision air line which serves as the impedance reference standard. The electrical length of this line, including connectors, is a multiple of one-half wavelength at the frequency of measurement.**

A slotted line and a termination, both having the same type connectors as those under test, are required. With the aid of an auxiliary slide-screw tuner, the slotted line and the termination are matched to each other. The output of the slotted line is then plotted by a graphic level recorder having an expanded-scale presentation and a mechanical linkage between the chart drive and the probe on the slotted line.

The section of air line fitted with the connectors under test is then placed between the slotted line and the termination, and a second curve is recorded. The slotted line and termination errors still cancel each other, and any errors due to variations in probe coupling along the line also cancel out. The difference between the initial curve and the second curve represents the mismatch of the connectors under test with respect to the precision air line. With a recorder having a scale expansion of 2 per cent full scale, VSWR's as low as 1.001 are easily discernible.

Introduction

Measurement of the VSWR or reflection coefficient of a pair of coaxial connectors has always been difficult because it is hard to separate the reflections due to the connectors from those due to the termination and from errors in the slotted line. In the following substitution method, the difference between the two successive measurements represents very closely the VSWR of a pair of connectors with respect to a section of precision air line that serves as the impedance reference standard. The most troublesome sources of error in the usual direct method, such as termination VSWR, residual VSWR in the slotted line, probe reflections, and variation in probe coupling are present in both substitution measurements to the same degree, and therefore cancel out in the final results to a first approximation. This technique has proved most useful in the development of new connectors. Its use has made possible the development of a new, high-precision connector for use from dc to 9 Gc with reflections an order of magnitude lower than those of any previous connector. Partly because of the lack of suitable measurement techniques, the nominal design of most widely-used coaxial connectors is far from optimum. Many commercially available connectors could be improved substantially without tighter tolerances, simply by changes in the nominal dimensions.

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The basic tools of this method are a slotted line and a graphic level recorder. These have been combined into one instrument, which presents a strip-chart recording of the standing-wave pattern on the slotted line. The chart drive is synchronized with the probe-carriage drive so that several different standing-wave patterns on the slotted line may be recorded on the same section of chart. The section of chart can then be removed and analyzed graphically to determine the magnitude and phase of the standing-wave patterns.

Such a "slotted-line-with-a-memory" is capable of much greater accuracy than the slotted line alone when used in the substitution method. Without the memory feature, the lack of flatness in the slotted line interferes with accurate determination of the position of the minimum and amplitude of the standing-wave pattern. At very low VSWR's, lack of flatness can prevent any measurement from being made because the sine wave variations that represent the desired signal are obscured by the variations in output owing to variations in probe coupling. However, these variations in coupling do repeat on successive passes of the probe carriage along the slotted line, and if the two curves of the substitution method are recorded, it is possible to subtract the curves graphically and obtain a good-looking sine wave when neither of the original curves resembles a sine wave at all. Therefore, the amplitude and phase of the difference curve, which are the quantities of interest in the substitution method, can be determined accurately by this method under circumstances that ordinarily would make a measurement impossible.

Description of Method

The measuring apparatus is illustrated in Fig. 1. The electrical length of the test section (reference air line plus unknown connectors) is a multiple of a half wavelength. This condition is obtained by adjusting the frequency until the positions of minima for a short-circuit termination are the same with and without the test section in place. For the initial adjustment, the termination is connected directly to the slotted line. The auxiliary slide-screw tuner, which in practice may be part of either the slotted line or the termination, is used to match one to the other, *i.e.*, to eliminate sinusoidal variations in the output of the slotted line. The probe is driven along the slotted line, and an initial curve (curve 1 of Fig. 2) is recorded on the strip chart. This curve would be a straight line but for variations in probe coupling.

Next, a short circuit is placed at the reference plane and the probe is driven along the line again, producing a

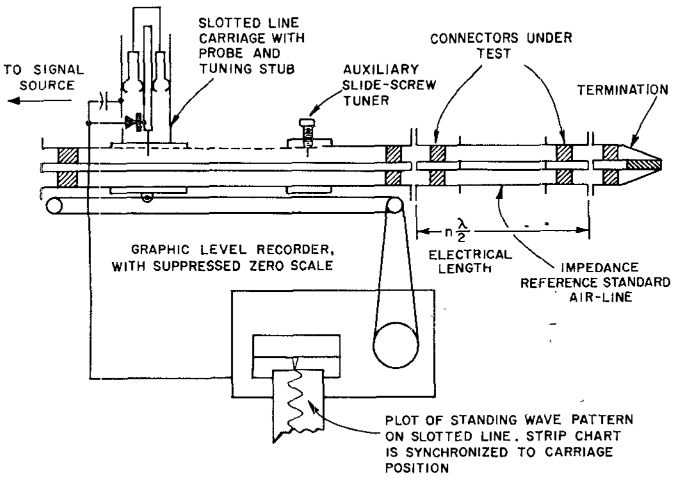

Fig. 1—Block diagram of measuring apparatus.

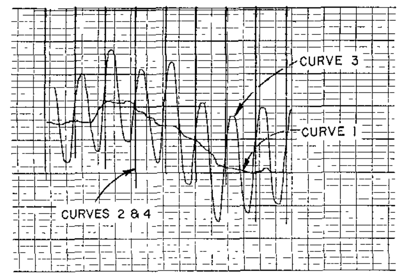

Fig. 2—Typical chart record taken at 8 Gc. Horizontal scale is 1 cm per division, vertical scale is 2 per cent full scale. Curve 1 is the initial condition; the difference between curves 1 and 3 is the VSWR of the connectors. Curves 2 and 4 are taken with a short circuit at the reference plane.

record of wavelength and position of minima on the slotted line. Connectors whose inner and outer conductors do not lie in one plane pose no special problem. The short circuit may be physically located at a distance from the junction of the two connectors. Then the positions of minima on the chart record are corrected by the distance between the physical short-circuit and the desired reference plane.

The test section is placed next between the slotted line and the termination, and a third curve is recorded. As a check on the fact that the electrical length of the test section is one-half wavelength, a fourth curve should be taken with the short circuit placed at the output end of the test section. The position of minima should be the same as before. The strip-chart record is now complete and may be removed for graphical analysis.

With a square-law detector and a linear recorder, the difference between curves 1 and 3 in Fig. 2 is sinusoidal, and the corresponding reflection coefficient may be plotted as a point on the Smith chart. As is shown in the Appendix, this point represents the reflection coefficient of the pair of connectors under test with respect to the characteristic impedance of the reference air line, and referred to the plane of the short circuit. This may be justified intuitively if one considers that the insertion of a reflectionless one-half wavelength section of transmission line of any constant characteristic impedance would, theoretically, cause no change in the standing-wave pattern. Therefore, any difference between the two curves can arise only if the connectors do not match the air line and thus cause internal reflections within the test section.

Discussion of Errors

The result of this measurement is an approximation, of course, but the degree of approximation is quite good. If the slide-screw tuner is associated with the slotted line, the error in the measured value of the reflection coefficient of the connectors due to these approximations depends on the reflection coefficient of the termination. If the tuner is part of the termination, the error depends on the reflection coefficient of the slotted line.

With the tuner part of the slotted line

$$0 \leq |\Delta\Gamma| \leq 4|\Gamma_l|(|\Gamma_x| + |\Gamma_y|),$$

where

Γ_x, Γ_y = reflection coefficients of unknown connectors
$\Delta\Gamma$ = error
$\Gamma_l = \Gamma$ of termination.

With the tuner part of the termination

$$0 \leq |\Delta\Gamma| \leq 4|\Gamma_m|(|\Gamma_x| + |\Gamma_y|),$$

$$\Gamma_m = \Gamma \text{ of measuring instrument.}$$

The maximum error is a constant percentage of $|\Gamma_x| + |\Gamma_y|$, and with reasonably low-reflection components, is negligible. For example, a slotted line with $\Gamma_m = 0.01$ (residual VSWR ≈ 1.02) and connectors having $\Gamma_x = \Gamma_y = 0.01$, could cause the measured reflection coefficient to be in error by a maximum of 0.0008.

Attenuation in the test section may cause some error in the measurement if the termination has a finite reflection coefficient. Between the first and the second measurements, the apparent reflection coefficient of the termination as seen by the slotted line is reduced by twice the amount of the attenuation in the test section. Thus, even if the connectors were perfect, there would be a reflection-coefficient reading with the test section in place. If the attenuation of the test section is A db, then the error in the measurement is given by

$$\Delta\Gamma \approx .23A\Gamma_l.$$

Since the test section can be quite short, on the order of a few half-wavelengths at the test frequency, the attenuation of the test section can easily be kept below 0.1 db, corresponding to an error less than 2.3 per cent of Γ_l.

The reflections within the test section can cause an error in setting the frequency to obtain an even multiple of one-half wavelength in the test section. The maximum angular error in radians in setting the electrical length, assuming the worst phase relationship between Γ_x and Γ_y, is

$$\Delta\theta = 2(|\Gamma_x| + |\Gamma_y|).$$

This angular error causes the phase of Γ_l to be rotated from the phase at which it cancelled the slotted-line error. It can be shown that the maximum resulting error is

$$0 \leq |\Delta\Gamma| \leq 4|\Gamma_l|(|\Gamma_x| + |\Gamma_y|).$$

The same sort of error arises if the test section is not set exactly to $n\lambda/2$ for any other reason. In order to estimate the accuracy with which this setting must be made, the following formula is given:

$$\Delta\Gamma = 2\Delta\theta\Gamma_l = 4\pi\frac{\Delta x}{\lambda}I_l,$$

where Δx is the deviation in the length from $n\lambda/2$. Note that this is an absolute error, and not a percentage error, so the setting is most critical when measuring low-reflection connectors, with a termination having a significant Γ_l.

In general it is better practice to make the tuner a part of the termination rather than of the slotted line, since the slotted-line residual reflection is usually smaller than the termination reflection. The initial tuning adjustment then ensures that the termination is as good as the slotted line, and minimizes the possible errors due to all of the above-mentioned causes.

The lowest VSWR that can be measured depends on the detector noise level. The noise level can be minimized by use of a good mixer crystal and a low-noise amplifier with high selectivity. With these precautions, the noise can be brought down to a level corresponding to a VSWR of 1.0001 to 1.0003, so that a VSWR of 1.001 is well above the noise level.

Results

The above method can be used to measure both coaxial and waveguide connectors. The following results were measured on a newly-developed coaxial connector having a Teflon bead support. The diameter of the outer conductor is 0.5625 inch, imposing an upper-frequency limit of about 9.3 Gc. Using a 15-cm test section, the connectors can be measured every 1 Gc up to 9 Gc. Fig. 2 is a typical chart record taken at 8 Gc. The results for a frequency run on a single pair of connectors over the range of 1 to 9 Gc are shown in Fig. 3. They are plotted both as points on an expanded Smith Chart and as a VSWR-vs-frequency run.

From the Smith Chart plot it is possible to determine that the behavior of this pair of connectors is correct theoretically. In this particular case, both connectors of the mated pair were identical, and the reference plane was chosen to be the centerline of a mated pair. Under these conditions the discontinuities are disposed symmetrically about the reference plane, and all the measured points should lie along the imaginary axis of the Smith Chart. From the distribution of points on the Smith Chart, it is possible to calculate what is wrong

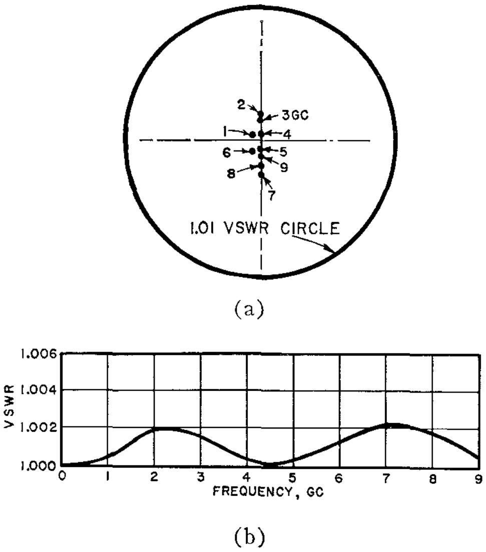

Fig. 3—Test data taken on a pair of precision coaxial connectors. (a) Smith Chart plot of data. (b) Same data plotted as VSWR vs frequency.

with a pair of connectors. In this particular case, the characteristic impedance of the connectors was too high by 0.1 per cent over an electrical length of 3.2 cm. This could have been corrected by an increase of 0.0002 inch in the diameter of the inner conductor over the corresponding physical length. Note that the phase information of the Smith Chart plot is essential to deriving this important design information. VSWR information alone is quite useless in trying to converge on a optimum design in the face of several independent variables such as are present in a coaxial connector with a bead support.

A noteworthy advantage of this technique is that a single slotted line and a single termination can be used over the entire frequency range of the connectors. At each frequency the auxiliary tuner must be set to match the slotted line to the termination, but, owing to the orthogonality of the two adjustments of the slide-screw tuner, this is accomplished easily and quickly.

Conclusions

The method presented here permits the measurement of the magnitude and phase of the reflection coefficient of coaxial connectors with or without bead supports. The magnitude of the reflection coefficient can be measured with a resolution of 0.0005 and an accuracy on the order of a few per cent. This compares favorably with the accuracy and resolution of a previous method[1] which is limited to the measurement of waveguide and coaxial connectors that do not have bead supports. However, the method described here is limited to the

[1] R. W. Beatty, "Measurements of reflections and losses of waveguide joints and connectors using microwave reflectometer techniques," IRE Trans. on Instrumentation, vol. I-9, pp. 219–226; September, 1960.

measurement of reflection coefficient, and is not adaptable to the measurement of connector losses. A practical advantage of this method is that a given test setup can be used to make measurements from a few hundred megacycles to the cutoff frequency of the slotted line.

This method has been applied to the design of a precision coaxial connector, and it has been found that connectors and bead supports can be designed and constructed with VSWR's smaller than 1.002 over the entire frequency range of the connector, *i.e.*, dc to just below the cutoff frequency. In the future it may be possible to do better, because no theoretical limitation has been reached, but only the practical limitations of holding mechanical tolerances and obtaining adequately smooth surface finishes.

Appendix

Analysis of Measurement Technique

The measurement technique can be analyzed through the use of signal flow graphs as described by Hunton.[2] The analysis assumes that the connectors and the reference air line are lossless, and that the reflection coefficients of all components are less than 0.1. These conditions are met easily in any practical system.

The equivalent circuit for the complete system is shown in Fig. 4, and the corresponding signal-flow graph is shown in Fig. 5. (Although the method described here uses a slotted line, the signal-flow graph analysis applies equally well to other measuring instruments.) Shurmer[3] has shown that "the properties of a lossless junction are uniquely defined by the complex value of reflection coefficient at a reference plane in the measuring line corresponding to matched conditions at the load, and that any such lossless system may therefore be represented by an equivalent system of a matched line with a reactance inserted at some particular plane." Therefore the susceptance B_m in the equivalent circuit of the slotted line simulates all the sources of error in the original slotted line that could cause it to read other than zero reflection coefficient when terminated in a matched load. This includes reflections from supporting beads, end of slot, and output connector, as well as an error in the characteristic impedance of the slotted section, and probe reflections interacting with a mismatched signal source. The equivalent circuit does not include the effect of variation in probe coupling, but this cancels out in the substitution method except for a small modulation effect. This modulation effect causes the amplitude of the sine-wave difference curve to vary by the same percentage as the probe coupling varies. Since the slotted line may easily be flattened to within 1 per cent over the section in use, the error from this source can be held to less than 1 per cent of the magnitude of the measured reflection coefficient.

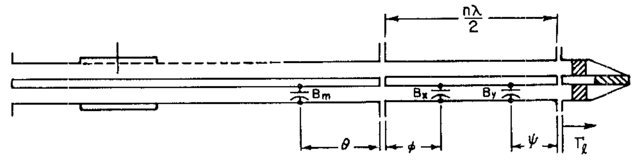

Fig. 4—Equivalent circuit for the analysis of the measurement technique. Shunt susceptances B_m, B_x, and B_y simulate the residual reflection of the slotted line and the reflections of the two unknown connectors.

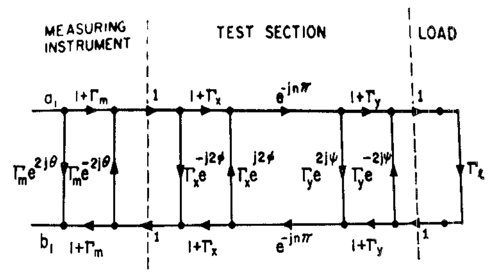

Fig. 5—Signal-flow graph corresponding to the equivalent circuit of Fig. 4.

The reflection coefficients of the unknown connectors are simulated with shunt susceptances located at particular positions along a one-half-wavelength section of constant-impedance transmission line. In the flow graph (Fig. 5), these three discontinuities have been transferred to the reference plane. All reflection coefficients are referred to the characteristic impedance of the precision air line, and the equivalent slotted line also has this characteristic impedance.

The reflection coefficient as measured by the equivalent slotted line must be determined for three conditions: 1) for the initial condition with the termination directly on the slotted line, 2) for the secondary condition with the connectors under test between the slotted line and termination, and 3) for the correct answer that would be obtained with a perfect slotted line and termination. By subtracting 1) from 2) and comparing this answer with 3), one can estimate the magnitude of the error.

The solution for the input reflection coefficient may be written by inspection, and all terms involving third- or higher-order products of Γ will be omitted under the assumption that no reflection-coefficient magnitude exceeds 0.1.

$$\Gamma = \frac{b_1}{a_1} = \Gamma_m e^{2j\theta} + \Gamma_x e^{2j\phi}(1 + 2\Gamma_m) + \Gamma_y e^{2j\psi}(1 + 2\Gamma_m + 2\Gamma_x) + \Gamma_l(1 + 2\Gamma_m + 2\Gamma_x + 2\Gamma_y), \quad (1)$$

[2] J. K. Hunton, "Analysis of microwave measurement techniques by means of signal flow graphs," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 206–212; March, 1960.

[3] H. V. Shurmer, "Transformation of the Smith chart through lossless junctions," *Proc. IEE*, vol. 105C, pp. 177–182; March, 1958.

where

$\Gamma_m e^{2j\theta}$ = reflection coefficient of measuring equipment referred to its output,

$\Gamma_x e^{-2j\phi}, \Gamma_y e^{2j\psi}$ = reflection coefficients of unknown connectors referred to ends of test section.

Γ_l = reflection coefficient of load referred to its input.

Γ_m, Γ_x, and Γ_y are the shunt susceptances in the equivalent circuit and have the form

$$\Gamma_m = \frac{-jB_m}{2 + jB_m}. \quad (2)$$

These susceptances are placed at electrical angles θ, ϕ, and ψ from the reference plane in the equivalent circuit.

The initial condition is obtained if Γ_x and Γ_y are made equal to 0 in (1). Denoting this by Γ', we have

$$\Gamma' = \Gamma_m{}^{2j\theta} + \Gamma_l(1 + 2\Gamma_m). \quad (3)$$

The difference between (1) and (3) is the apparent connector-reflection coefficient

$$\Gamma - \Gamma' = \Gamma_x e^{-2j\phi}(1 + 2\Gamma_m) + \Gamma_y e^{2j\psi}(1 + 2\Gamma_m + 2\Gamma_x) + \Gamma_l(2\Gamma_x + 2\Gamma_y). \quad (4)$$

The true reflection coefficient of both connectors can be obtained if Γ_m and Γ_l are made equal to zero in (1). Denoting this by Γ'', we have

$$\Gamma'' = \Gamma_x e^{-2j\phi} + \Gamma_y e^{2j\psi}(1 + 2\Gamma_x). \quad (5)$$

Subtracting (5) from (4) gives the absolute error in measuring the reflection coefficient of the pair of connectors.

$$\Delta\Gamma = \Gamma - \Gamma' - \Gamma'' = 2\Gamma_m\Gamma_x e^{-2j\phi} + 2\Gamma_m\Gamma_y e^{2j\psi} + 2\Gamma_l\Gamma_x + 2\Gamma_l\Gamma_y. \quad (6)$$

This is a vector relationship, and it is very unlikely that all the vectors would add up in phase to yield the maximum possible error. However, the maximum value of the above expression is the sum of the magnitudes of the four individual vectors, and the minimum value is zero when the vectors happen to cancel. Therefore,

$$0 \le |\Delta\Gamma| \le 2(|\Gamma_m| + |\Gamma_l|)(|\Gamma_x| + |\Gamma_y|). \quad (7)$$

The error is a constant percentage of the sum of the reflection-coefficient magnitudes of the two connectors, and therefore reduces to zero with perfect connectors.

This is the maximum error in the measurement if no attempt is made to match the slotted line to the termination. If they are matched, then $\Gamma' = 0$ and from (3)

$$|\Gamma_m| \approx |\Gamma_l|. \quad (8)$$

Substituting (8) in (7),

$$0 \le |\Delta\Gamma| \le 4|\Gamma_l|(|\Gamma_x| + |\Gamma_y|) \quad (9)$$

or

$$0 \le |\Delta\Gamma| \le 4|\Gamma_m|(|\Gamma_x| + |\Gamma_y|). \quad (10)$$

If the tuner is part of the slotted line, then the reflection coefficient of the termination is the governing factor in the accuracy of the measurement, and (9) applies. If a tunable termination is used, then the residual error in the slotted line is the governing factor and (10) applies.