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AN ACCURATE SUBSTITUTION METHOD OF MEASURING THE VSWR OF COAXIAL CONNECTORS

by

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AN ACCURATE SUBSTITUTION METHOD OF MEASURING THE VSWR OF COAXIAL CONNECTORS

Introduction

One of the most vexing problems facing the microwave design engineer who must make accurate measurements of reflection coefficient or VSWR in coaxial systems is the limitation imposed by the connectors. In standard military types of coaxial connectors at microwave frequencies, the industry considers a VSWR of 1.1 quite good, and a VSWR of 1.05 about all that one can possibly expect of the present state of the art. This means that the VSWR of the connectors is often the limiting factor in the performance of microwave instruments and equipment. For example, coaxial slotted sections can be designed with residual VSWR's far below the VSWR of any presently available connector, and it is also possible to design terminations that are better than the connectors themselves. Faced with the necessity of using connectors with a substantial VSWR, the average design engineer carries his design to the point where the VSWR of the component including connectors is roughly the same as the VSWR he expects from the connectors alone. There is no point in going any further. To achieve any further reduction in over-all VSWR he must distort the design of the component to compensate for the connector's deficiencies, a "solution" that is effective only over a narrow frequency range.

Since connectors are the bottleneck both in the design of microwave components and in the accuracy of measuring equipment, one naturally wonders what factors prevent connectors from being any better. Is it necessary to tighten tolerances on the individual pieces? Does a highly variable dielectric constant of the bead supports cause high VSWR? The culprit is neither of these factors, but is the fact that the nominal designs of almost all commonly used connectors are far from optimum. This leads to high VSWR's which have no relation to the variability of the individual parts, and which could easily be corrected by small changes in the nominal dimensions. For example, the standard military type BNC connector has a VSWR that rises to about 1.1 at 2 Gc and stays at 1.1 to 6 Gc. The design of this connector was optimized at General Radio for use in an adaptor from another connector type to BNC, and the worst source of error was found to be the diameter of the inner conductor. Nominal diameter of this piece was 0.083 $\pm$0.001 inch, and to achieve an optimum result, this had to be increased to 0.088 inch. When this change and some smaller ones were made, the VSWR dropped to 1.01 to 4 Gc and 1.04 to 6 Gc. It should be noted that this optimum-design connector would have been a reject according to the standard drawings since 0.088 is outside the tolerance of 0.083 $\pm$0.001. In redesigning types N, TNC, HN, C and others for minimum reflections, the same situation has been found.

A possible reason that these connectors were not of optimum design was the lack of an accurate method of measuring low VSWR's. Designing connectors is a sort of a bootstrap operation, since before you can design a good connector, you have to have both a good slotted line and a good termination with which to measure it. On the other hand, before you can design a good slotted line and termination, you need good connectors to put on them. The substitution method of measuring the VSWR of connectors to be presented here breaks this vicious circle by separating the connector errors from the errors in the measuring equipment and termination. Connector VSWR's of the order of 1.001 can be measured with slotted lines and terminations having VSWR's of the order of 1.1 or less. The trick is to make two measurements of reflection coefficient, one with the connectors under test in the circuit and one with them out of the circuit. Under the conditions discussed below, the difference between the two results represents the reflection coefficient of the connectors under test, while the sources of error in the measuring equipment and the termination cancel out.

The availability of a simple and convenient method of measuring the VSWR of coaxial connectors can lead to better connectors. The barrier to better connectors is mental, not physical. Engineers have become accustomed to thinking that a VSWR of 1.1 is acceptable in a coaxial connector, but there are very few other fields of engineering in which an accuracy of 10% in a measurement is considered acceptable. Better connectors are possible, and with the present state of the art, most commonly used connectors can be improved by an order of magnitude.

Figure 1 — Test setup for measuring connector VSWR. Output of slotted line is fed to recorder which plots the standing-wave pattern on strip chart. The standard half-wave section of air line with connectors and termination can be seen at the right-hand end of the slotted line.

Description Of Method

The instrumentation required by this test method consists of a slotted line and a graphic level recorder, which are linked together so that the recorder presents a strip-chart recording of the standing-wave pattern of the slotted line. Photographs and a semischematic drawing of the test setup are shown in Figures 1 and 2. The connectors under test are mounted, as shown in Figure 3, on short sections of precision air line for the most precise measurements; for measuring cable-to-cable VSWR, the connectors may be mounted on a section of coaxial cable. This section of air line or cable serves as the impedance reference standard for the measurement and so should be made or selected with great care. The electrical length of the test section (coaxial line plus two connectors) should be one-half wavelength at the lowest frequency at which measurements are desired, or at the minimum spacing frequency between measurements, whichever is the lower. Measurements can be made with one test section at all integral multiples of the frequency at which the electrical length is one-half wavelength. For example, connectors mounted on a test section 30 cm long can be measured every 500 Mc up to the cutoff frequency of the slotted line or connector under test, whichever is lower.

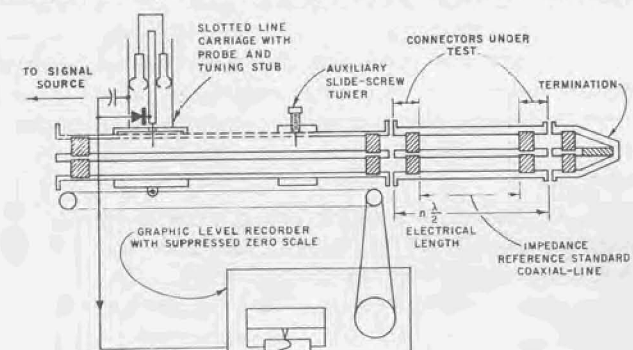

Figure 2 — Block diagram of test setup for measuring connector VSWR.

The slotted line and termination should be fitted with the same type of connector as those used on the test section, or with adaptors to this type of connector. Critical dimensions on the mating parts should be checked to make sure that the engagement of the spring fingers and contacts of all four connectors is the same, so that any gaps, such as those in the inner conductor of type N connectors, will be the same for all possible combinations of mated pairs in the test setup. It should be emphasized that the four connectors need not be the same electrically, but they must mate with each other in a mechanically identical manner in order for the substitution method to be valid.

The generator driving the slotted line is square-wave modulated at an audio frequency. The audio output of the detector of the slotted line is fed to a graphic level recorder having a suppressed-zero chart presentation. A typical chart record is shown in Figure 4. The motor in the recorder that drives the strip chart is linked to the slotted-line probe carriage with a positive chain drive, so that the standing-wave pattern on the line can be recorded for several different terminating conditions on the same section of chart paper. Recording the output of a slotted line in this manner greatly increases its capability for making accurate measurements. Since all the curves are recorded for one direction of probe travel, backlash in the carriage drive has no effect. The position of minimum can be located much more accurately on a chart of the complete standing-wave pattern than it can by manual means. It is also much easier to separate the effects of slope and irregularity in probe pickup from the sinusoidal variations due to true reflections when the whole standing-wave pattern is visible at a glance. Therefore, the graphic record leads to a more accurate value for the magnitude of standing-wave pattern as well as for the phase.

After the test section has been constructed and the slotted line and termination equipped with the same type of connectors, the next step is to make a recording of the standing wave pattern with the termination plugged directly onto the slotted line and with the auxiliary slide-

Figure 3 — Connectors under test are mounted on short sections of precision air line which serve as the impedance reference standard. Left to right, precision 50-ohm termination used in the measurements, GR Type 900 Precision Connector, GR Type 874 Connector, and Type N Connector.

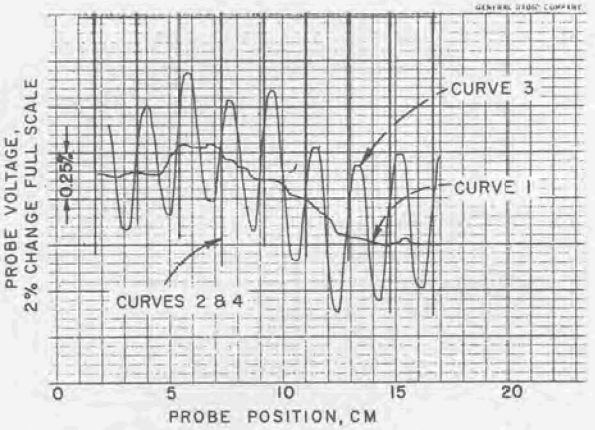

Figure 4 — Typical chart record taken at 8 Gc. Peak-to-peak amplitude of curve 3 minus curve 1 equals the VSWR of unknown connectors.

screw tuner decoupled. The tuner is then adjusted to cancel out this initial reflection, so that the standing-wave pattern is flat except for variations due to nonuniformity in the probe coupling. A convenient method of adjusting the tuner is as follows: With the probe carriage stationary, the penetration of the tuner is set so that sliding the tuner along the line produces a peak-to-peak change in output equal to that produced in the initial measurement of the termination alone. The magnitude of the reflection from the tuner is now correct, and to get the phase right, the tuner is positioned, with the probe carriage moving, for minimum VSWR on the slotted line. Further small changes in penetration and position may be necessary to get the slotted line as flat as possible. However, it is necessary to tune only until the residual VSWR is small compared with the expected VSWR of the connector pair under test, a matter determined by experience.

After the tuning adjustment, the curves shown in Figure 4 are recorded on a fresh section of the chart paper. Curve 1 is the standing-wave pattern with the termination directly on the slotted line after the tuning adjustment. Curve 3 is the pattern with the test section in place between the slotted line and the termination. The spikes (curves 2 and 4) represent the positions of minima on the slotted line with a short circuit at the reference plane. To record sharp spikes the audio gain should be increased by about 30 db with the short circuit in place. To make sure that the electrical length of the test section is in fact one-half wavelength, the positions of minima should be recorded both with the reference short circuit on the slotted line directly, and with the test section in place between the short and the slotted line. The positions of minima must be the same in either case.

It can be shown[1] that the difference between curves 1 and 3 in Figure 4 represents very closely the VSWR of the connectors under test with respect to the characteristic impedance of the line on which they are mounted. The phase of the mismatch is determined by a measurement of the position of minimum of the difference curve with respect to the short-circuit spikes. This refers the measurement to the plane of the physical short circuit. If some other reference plane is preferable, the easiest way to move the reference plane is to draw on the chart paper a new reference plane separated from the spikes by the electrical distance between the physical short circuit and the desired reference plane.

The intuitive justification for this method is as follows: The input impedance of a one-half wavelength section of transmission line of any characteristic impedance is the same as its terminating impedance. Therefore, if there are no internal reflections within the test section, that is, if the connectors under test match the characteristic impedance of the coaxial line on which they are mounted, the slotted line sees the same terminating impedance under both conditions of measurement. If there is some difference between the two measurements, it means that the two connectors do not match this section of coaxial line, and the difference between the two curves is a measure of this mismatch.

The one-half-wavelength condition is beneficial in another way. Since the two connectors are separated by a multiple of one-half wavelength, they are in the same relative position with respect to the reference plane as they would be if they were plugged into each other. This means that the result of the measurement is the reflection coefficient of the two connectors measured as a mated pair. The fact that the two connectors do not happen to be mated to each other is unimportant as long as all four connectors mate with each other in a mechanically identical manner.

Brief Theory Of The Method

The complete theory of the method, with formulas for the errors introduced by the approximations, is presented in reference 1. However, a vector analysis on the reflection-coefficient plane, although not rigorous, does show how the method works to a first approximation, and the approximations involved all approach zero as the reflection coefficients of the unknown connectors approach zero. This approach assumes that the total reflection coefficient due to a number of reflections is equal to the vector sum of the individual reflection coefficients taken one at a time.

The reflection-coefficient vector diagram corresponding to the initial condition is shown in Figure 5a. Γ_m is the error in the measuring equipment, which may be a slotted line, a Smith chart impedance plotter, or any other instrument which measures complex reflection coefficient. Γ_m is the false reflection coefficient that the measuring equipment would measure if terminated in a load having a reflection coefficient of zero. The reflection coefficient of the load is called Γ_l, and the reflection coefficient of the auxiliary slide-screw tuner Γ_t. Initially, the tuner is adjusted so that its reflection coefficient is equal in magnitude and opposite in phase to the sum of Γ_m and Γ_l, so that the total of these three reflections is zero. The secondary condition with the connectors under test between the measuring equipment and the termination is shown in Figure 5b. Depending on the electrical length of the test section, the phase of Γ_l will be different from that in the initial measurement. The phases of Γ_m and Γ_t will be the

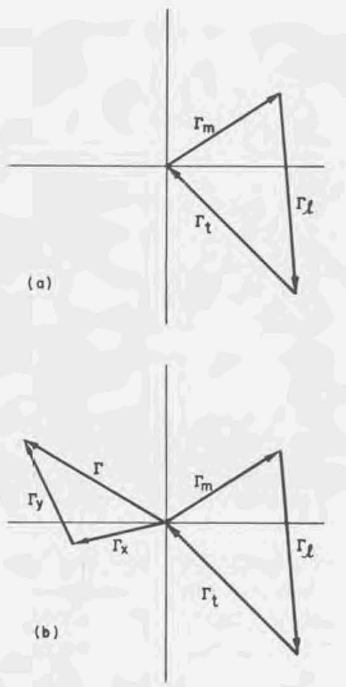

Figure 5 — Vector diagram for analysis of method of measurement.

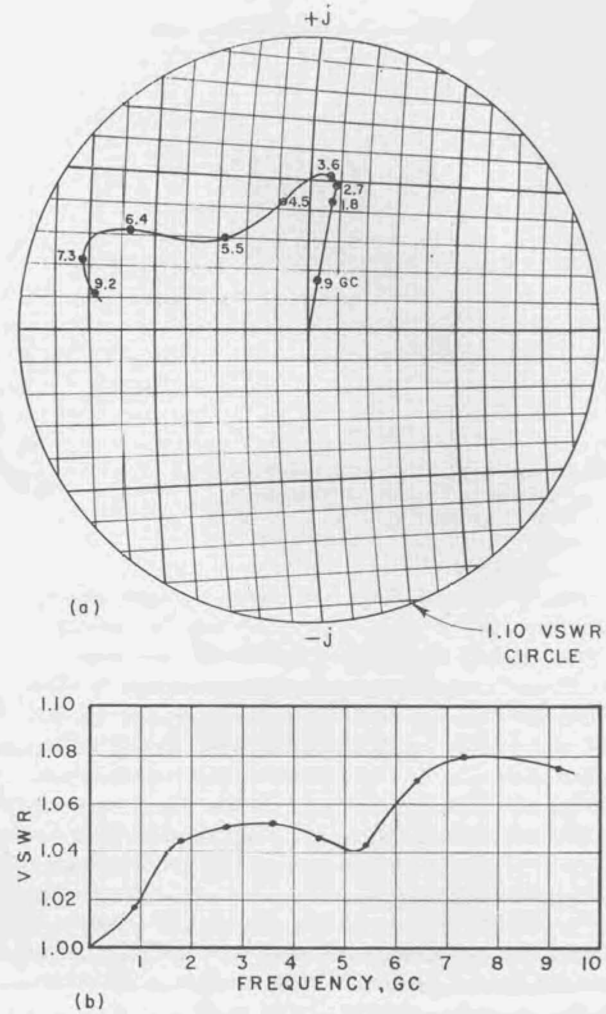

Figure 6 — Measurements of modified Type N connectors. (a) Smith chart plot; (b) Corresponding VSWR plot.

same, however. If the frequency is adjusted so that the electrical length of the test section is a multiple of one-half wavelength, Γ_l can be brought back to its original phase so that it cancels Γ_m and Γ_t. The only remaining uncanceled reflections are Γ_x and Γ_y, the reflections from the two unknown connectors. The measuring equipment measures Γ, the vector sum of Γ_x and Γ_y.

The effect of small misadjustments in the tuner can be compensated for if the vector difference between initial and secondary measurements is taken rather than the secondary curve alone. This can be seen easily from a vector diagram for this case.

The most important errors in the measurement are second-order effects dependent on the reflection coefficients of the unknown connectors and the load. They can cause an error in setting the frequency, and they interact with the other reflections to produce errors. The maximum resulting error, $\triangle\Gamma$, is

$$|\triangle\Gamma| = |\Gamma_l| \; (|\Gamma_x| + |\Gamma_y|)$$

assuming the tuner to be mounted on the slotted line. It can be seen that the error goes to zero as the reflection coefficients of the unknown connectors approach zero.

Results Of Measurements

Three sets of measurements were selected to represent a range of measurement problems that might be encountered in practice. All measurements were made on a test setup equipped with experimental GR Type 900 Precision Connectors, and only one slotted line and one termination were required to cover the entire frequency range. Adaptors were used on the slotted line and termination to make measurements on other types of connectors. The time required to make and plot a complete set of measurements on a given pair of connectors was about four hours.

The impedance standard for these measurements was a section of 50.0-ohm $\pm 0.1\%$ air line having nominal inner and outer diameters of 0.2442 and 0.5625 inch respectively.

Figure 6 shows measurements made on a pair of modified Type N Connectors, and includes the effect of a stepped transition to the diameter of the air line in both the male and female connectors. Changes have been made in these N connectors to reduce the VSWR. The reference plane for the measurement was the outermost shoulder in the male inner contact pin, and the male connector was on the load side of the reference plane. The contact gap between the male and female inner contacts on these connectors was 0.026 inch, which is just about nominal for the Type N Connector. An analysis of the Smith chart plot shows the inductance of this gap to be the predominant source of reflections in the connectors.

The data in Figure 7 were obtained on a pair of experimental GR Type 874 Connectors. These connectors can be mounted directly on the 0.5625-inch air line, and the electrical length of the test section was preadjusted to

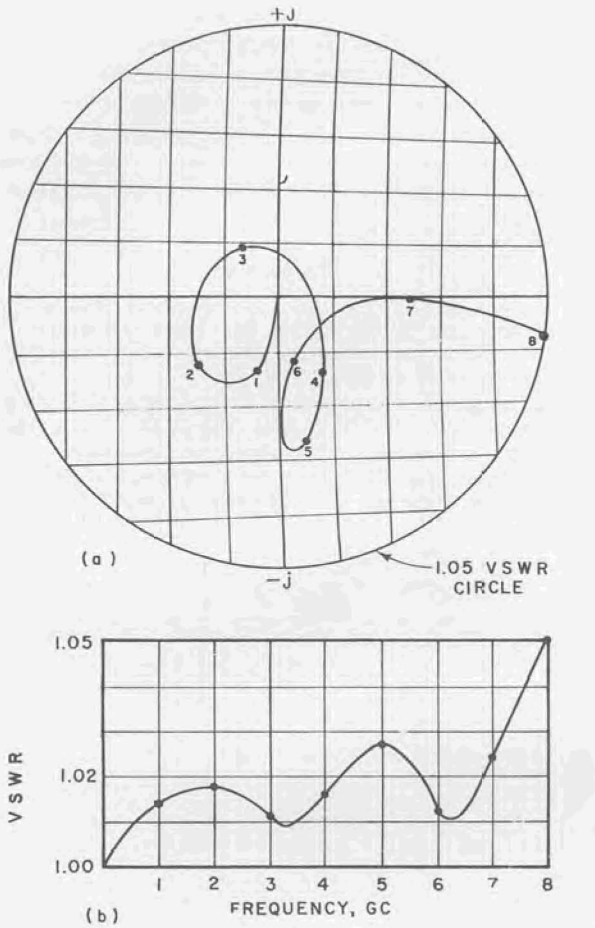

Figure 7 — Measurements of a pair of experimental GR Type 874 Connectors. Scale is twice the scale of Figure 6.

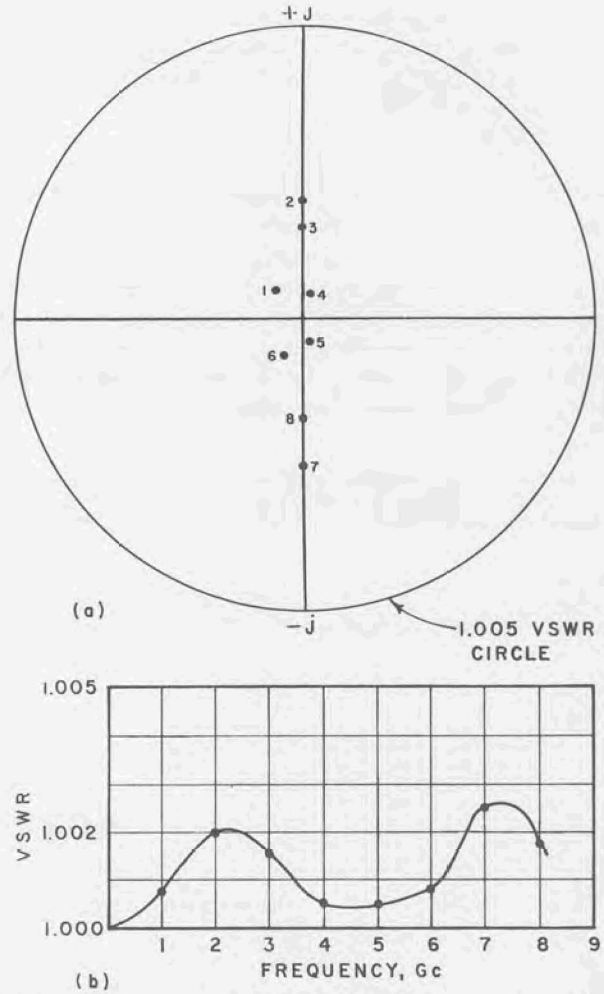

Figure 8 — Measurements of a pair of experimental GR Type 900 Precision Connectors. Scale is twenty times the scale of Figure 6.

be exactly 15 cm so that the test frequencies would fall at intervals of 1 Gc. The reference plane for this measurement was the face of the bead nearest the generator so that the reflections are all on the load side of the reference plane. The reflection coefficient curve must therefore rotate always in the clockwise direction. An analysis of this curve shows the predominant reflections to be two capacitive discontinuities in the two bead supports. Considering the physical structure of the connector, this seems reasonable because of the corner capacities of the step changes in diameter going through the bead.

In order to show the resolution of small reflections possible with this method, the data of Figure 8 are presented, showing measurements on an experimental precision connector, the GR Type 900 previously mentioned. These connectors mount directly on the 0.5625-inch air line. These data are plotted on an expanded Smith chart having a VSWR of 1.005 full scale. The reference plane was the centerline of a mated pair of connectors, and since this is a sexless connector and the discontinuities are symmetrically disposed about the reference plane, all the points of the measurement should fall on the vertical (imaginary) axis. Since this is very nearly true on the plot, it proves that the two connectors being measured are very nearly identical.

Even though the VSWR of these connectors does not exceed 1.003 over the band from dc to 8 Gc, they are still not optimum. An analysis of this reflection-coefficient curve shows that the characteristic impedance of the connectors was too high by 0.1 per cent over an electrical length of 3.2 cm centered about the reference plane. This corresponds to an error in the diameter of the inner conductor of 0.0002 inch in a nominal diameter of 0.244 inch. The nominal design of this connector can be determined to the nearest 0.0001 inch on dimensions of metal parts — only slightly less accurately for the bead supports — and should result in a connector with a design center VSWR of 1.001 from dc to 9 Gc. The only problem, of course, is holding mechanical tolerances so as to make such a fine design meaningful, and it is expected that the tolerances will determine the test limits on VSWR for this connector, rather than limitations in the design of the "nominal" connector.

Conclusions

With the method presented here, measurements of VSWR or reflection coefficient of a pair of connectors joined to either an air- or dielectric-filled line can be made conveniently over a wide frequency range and on all types of coaxial connectors using a single test setup. The resolution and accuracy of the method are such that it is quite possible to perfect the design of a given connector to the point where the mechanical tolerances prove to be the limiting factor in the performance that can be achieved, rather than reflections built into the nominal design.

Since this method yields the phase of the reflection coefficient as well as the magnitude, it is possible to analyze the data obtained and determine the exact nature and position of the discontinuities present in the connector.* Perfecting a given connector is then simply a convergence problem, in which the connector is alternately measured and corrected, measured and corrected until the performance is limited by tolerances or some other factor over which the design engineer has no control. In any case, the limiting factor should no longer be the inability of the design engineer to measure and resolve small reflections in the unknown connectors in the presence of sizable reflections and errors in the measuring equipment.

* *Methods of analyzing this data will be covered in a paper by A. P. Lagon entitled, "VSWR Considerations In Precision Coaxial Connector Design."*

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