CALIBRATING TWO SIX-PORT REFLECTOMETERS WITH AN UNKNOWN LENGTH OF PRECISION TRANSMISSION LINE

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ABSTRACT

This paper describes a technique for calibrating a pair of 6-port reflectometers for measuring the complex reflection coefficient of 1-port devices, or the scattering parameters of reciprocal 2-port devices. The operations in the calibration consist of connecting the two 6-ports together, connecting each 6-port to a calibration circuit consisting of two unknown terminations and a leveling loop, and then connecting the standard. The standard can be one termination whose complex impedance is known, or a length of precision transmission line whose cross-sectional dimensions are known. The length and loss of the line are not required. The solution for the constants which characterize each 6-port is closed, requiring no iteration.

Introduction

A 6-port reflectometer can be used to measure the complex impedance or reflection coefficient of a 1-port device connected to its reference plane [1]. It will also measure voltage, current, or power at that reference plane. Two 6-port reflectometers can be used to measure all of the scattering parameters of a 2-port device which is inserted between the two reflectometers as shown in figure 1 [2]. This paper describes a technique for calibrating a pair of 6-port reflectometers for making all of these measurements.

Each 6-port reflectometer can be characterized by a square matrix containing 16 real constants. Although only 12 of these 16 constants are independent, the mathematics is simplified by using all 16. The objective of the calibration is to determine these two matrices which will be called $\underset{\sim}{H}_1$ and $\underset{\sim}{H}_2$ corresponding to 6-port #1 and 6-port #2.

The calibration procedure is described here without referring to any equations. The equations and their derivation are being published in an NBS Tech Note [4] which includes a review of 6-port reflectometer equations expressed in matrix notation. The solution for the constants contained in $\underset{\sim}{H}_1$ and $\underset{\sim}{H}_2$ is given in detail using matrix algebra whenever possible. An appendix gives computer program outlines for taking and processing the calibration data.

The calibration technique described in this paper is similar to that described by Allred and Manney for calibrating two 4-port couplers [3]. The solution is a closed solution, requiring no iteration.

Outline of Calibration Procedure

The calibration consists of two parts. The first part uses no standards and obtains enough of the constants in $\underset{\sim}{H}_1$ and $\underset{\sim}{H}_2$ to make impedance ratio measurements at either 6-port reference plane. The second part of the calibration requires the use of one impedance standard to find the remaining constants needed in measuring absolute impedance or reflection coefficient.

The first part of the calibration consists of the following three operations which are illustrated in figure 2.

1. The two reference planes are connected together and all 6-port sidearm power readings are recorded at four or more different settings of A_1, A_2 and ϕ. The values of attenuation A_1, A_2 and the value of phase ϕ do not need to be known. This set of measurements is sufficient to determine $\underset{\sim}{H}_2$ in terms of $\underset{\sim}{H}_1$, thereby reducing the number of unknowns from 32 to 16. If 6-port #1 is already calibrated so that $\underset{\sim}{H}_1$ is known, then this set of measurements is sufficient to calibrate any other 6-port.

2. Six-port #1 is connected to the calibration circuit shown in figure 2b and its sidearm power readings are recorded at each of the two switch positions within the calibration circuit. P_c is either recorded or held constant by leveling the generator.

3. Six-port #2 is connected to the calibration circuit and its sidearm power readings are recorded as in step 2. P_c is again either recorded or held constant by leveling the generator.

To make the connections in steps 1 to 3 requires that all connectors be of the same sexless type. The impedance of the two terminations in the calibration circuit need not be known. It is assumed only that 6-port #2 sees the same two different impedances when connected to the calibration circuit as 6-port #1 sees when it is connected to the calibration circuit. This requires that the switch in the calibration circuit be repeatable when using the measurement sequence 1-3 above. However, this requirement can be eliminated by connecting each 6-port to the calibration circuit when the switch is in position e, and again connecting each 6-port when the switch is in position f.

Steps 2 and 3 are sufficient to reduce the number of unknowns from 16 to 8. Half of the constants in $\underset{\sim}{H}_1$ are given in terms of the other half. The remaining 8 unknown constants are reduced to just 3 unknowns by taking advantage of the dependent relationship between the constants. It can be shown that these three remaining unknown constants are not needed for calculating the impedance ratio of two terminations. Therefore the set of measurements described in steps 1 to 3 which uses no standards is sufficient to calibrate each 6-port for making impedance ratio measurements.

The second part of the calibration uses one impedance standard to find two of the three remaining unknown constants in $\underset{\sim}{H}_1$ and $\underset{\sim}{H}_2$. These two constants are needed to calculate absolute impedances or reflection coefficients from which S-parameters of 2-port devices are calculated. The standard can be a uniform length of transmission line which is inserted between the two 6-ports as shown in figure 3. With the line inserted, all 6-port sidearm power readings are recorded at two or more different settings of A_1, A_2, and ϕ. As in step 1 above, the values of A_1, A_2, and ϕ do not need to be known. This set of measurements is sufficient to determine the two needed constants and also $\gamma\ell$ of the line, where γ is the complex propagation constant of the line and ℓ is its length. The length and loss of the line do not need to be known, only its cross-sectional dimensions need be known.

The standard can also be a termination whose complex reflection coefficient is known. With this standard connected to either 6-port, the sidearm power readings for that 6-port are recorded. The two needed constants are calculated from this set of readings and the known value of reflection coefficient.

The last remaining unknown constant in $\underset{\sim}{H}_1$ and $\underset{\sim}{H}_2$ is determined only if each 6-port is to be used for measuring voltage, current, or power in addition to passive circuit parameters. To determine this last constant, a power standard is connected to either 6-port reference plane as indicated in figure 3. The sidearm power readings of that 6-port as well as the reading of the power standard are recorded. The last constant in $\underset{\sim}{H}_1$ or $\underset{\sim}{H}_2$ is calculated from this set of readings. All constants in $\underset{\sim}{H}_1$ and $\underset{\sim}{H}_2$ are now known so that either 6-port can be used to measure active as well as passive circuit parameters.

Practical Considerations

When the reference planes are connected together, the values of a_2/a_1 at the common reference plane must not all have the same magnitude or all have the same phase, or certain matrices in the solution become singular. In the present NBS dual 6-port ANA 4 to 6 measurements are taken with A_1, A_2, and ϕ in figure 1 set so that a_2/a_1 at the common reference plane is approximately equal to 1 at -90°, 1 at 180°, 1 at 0°, 0.3 at 90°, 1 at 90°, and 0.3 at -90°.

One purpose of the two terminations in the calibration circuit is to define the measurement reference planes, so these two terminations should be highly reflecting. In the present NBS dual 6-port ANA one termination is a short and the other is an open circuit cap. The directional coupler in figure 2b is a 3 dB power divider. The reflection coefficient looking into the calibration circuit is then approximately 0.5 with two different phase angles which are about 180° apart.

When the standard transmission line is inserted, two to four measurements are taken by changing ϕ only since there is then no restriction on the values of a_2/a_1 requiring that their magnitudes not all be the same. The phase shifter ϕ is set so that a_2/a_1 is approximately equal to 1 at 90°, -90°, 0°, and 180°.

The length of the standard transmission line must be chosen so that it is not too near a multiple of half-wavelengths long at the frequencies of operation. One way of choosing the length is illustrated in figure 4. If the 6-ports are designed to operate over the frequency range f_1 to f_2, the length of line is chosen so that it is a half-wavelength long at the frequency $f_1 + f_2$. If the phase shift through the line relative to 180° is too small near f_1 and f_2, one or more additional lines may be needed. The lengths of these additional lines are chosen to be integral multiples of the first line length.

For example, to operate over the 2 to 18 GHz range, $f_1 + f_2 = 20$ GHz. For a coaxial system, a length of air line 0.75 cm long is a half wavelength at 20 GHz, so 0.75 cm would be a preferred length. This line would have a minimum effective phase shift of 18° at both 2 and 18 GHz. If this phase shift is considered to be too small, a second line three times as long as the first (2.25 cm) would increase the minimum effective phase shift to 45° as shown by the shaded accent in figure 4. The shorter line would be used from 5 to 15 GHz, and the longer one outside of this range.

References

[1] Engen, G. F., The six-port reflectometer: An alternative network analyzer, IEEE Trans. Microwave Theory Tech., Vol. MTT-25, pp. 1075-1080 (Dec. 1977).

[2] Hoer, C. A., A network analyzer incorporating two six-port reflectometers, IEEE Trans. Microwave Theory Tech., Vol. MTT-25, pp. 1070-1074 (Dec. 1977).

[3] Allred, C. M., and Manney, C. H., The calibration and use of directional couplers without standards, IEEE Trans. Instrum. Meas., Vol. IM-25, pp. 84-89 (March 1976).

[4] Hoer, C. A., Calibrating two 6-port reflectometers with only one impedance standard, NBS Tech. Note 1004, 37 pp. (1978).

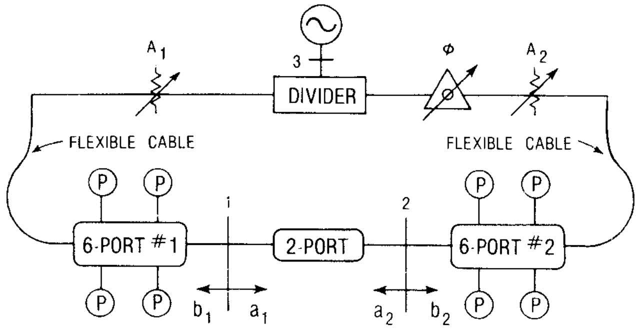

Figure 1. Using two 6-port reflectometers to measure all of the scattering parameters of a 2-port device.

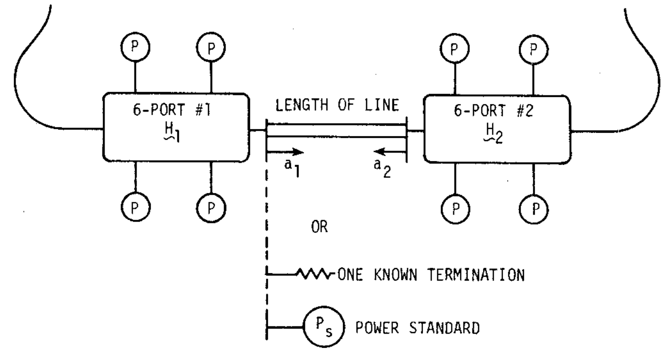

Figure 3. A uniform length of transmission line or one known termination is the only impedance standard needed. A power standard is connected to one of the 6-port reflectometers to calibrate them for making absolute power measurements.

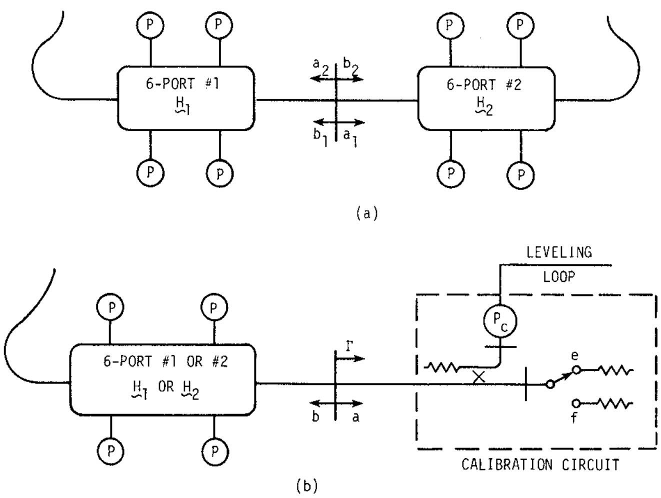

Figure 2. The first part of the calibration consists of connecting the two 6-port reference planes together (a), and then connecting each 6-port to a calibration circuit (b). The output P_c of the directional coupler is either measured or held constant by leveling the generator. The two different terminations e and f need not be known.

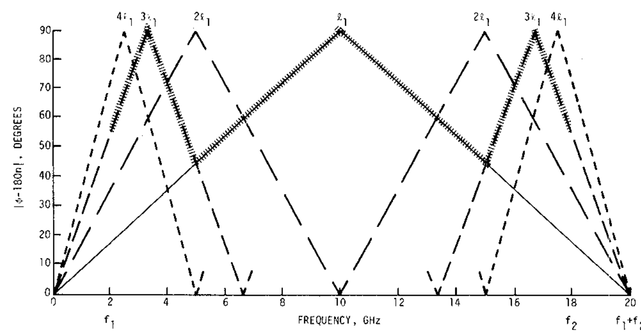

Figure 4. Effective phase shift through standard transmission lines as a function of frequency where ϕ is the actual phase shift through the line and n = 0, 1, 2,.... The line lengths are chosen so that they are multiples of a half wavelength at $f_1 + f_2$, where f_1 and f_2 are the frequency limits of operation of the 6-ports. For coaxial air lines,

$$\phi = 12\, f_{GHz}\, \ell_{cm} \quad \text{degrees}$$

and

$$\ell_1 = \frac{15}{f_1 + f_2} \quad \text{cm for f in GHz.}$$