CALIBRATING THE SIX-PORT REFLECTOMETER

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ABSTRACT

Because complex heterodyne methods may be replaced by simple amplitude detectors, the six-port technique promises to have a major impact on the next generation of automatic network analyzers. This projection, however, is predicated upon the existence or development of calibration techniques which permit one to conveniently and accurately obtain the parameters which characterize the six-port.

This paper describes a number of substantial refinements to a previously described procedure which is based upon the use of sliding terminations.

Introduction

The appeal of the six-port measurement concept stems largely from the simplification which it affords in the associated detection circuitry. Instead of complex heterodyne schemes, simple diode, thermoelectric, or bolometric type detectors are all that is required. Because frequency conversion and mixing have been eliminated, practical experience, to date at least, indicates that a high order of stability in the source frequency (e.g., a frequency synthesizer) is not essential, (although it certainly may be useful!). Moreover, recent theoretical work has yielded an improved physical insight into the method so that it may now be applied with greater confidence[1].

The development of calibration techniques, which permit one to conveniently and accurately obtain the parameters which characterize the six-port, however, underlies the projected applications. Although the calibration task does not pose any problems of a fundamental character, the supplementary requirements for convenience and speed (while not sacrificing accuracy), together with the general constraints imposed by an automated environment, combine to form the major challenge associated with the method.

As contrasted with the four-part reflectometer (which provides the basis for the existing network analyzers), the six-port reflectometer requires eleven rather than six constants for its calibration. Given this information, one might anticipate that the number of required terminations or standards, and thus operator and computational effort, would perhaps also be doubled. While this is nominally true of the computational effort, the procedures can still be handled by a desk-top programmable calculator.

Fortunately, this calibration scheme, along with others that have been described, is only slightly more involved in terms of operator effort than that for a four-port device. When coupled with the projected long-term stability of the calibration results, it appears that the total calibration effort associated with a six-port measuring system may ultimately become substantially less than that for a four-part.

Theory

Referring to the six-port in Figure 1, arms 3...6 have been terminated by power meters while the measurement objective is to determine the complex impedance and/or power level at port 2. Here it is convenient, as also suggested in an earlier paper[2], to take the point of view that the role of detectors 5 and 6 is to restore or otherwise provide the phase information in the complex ratio between the wave amplitudes b_3, b_4 which has been lost or forfeited as a consequence of using power detectors to terminate these arms rather than a complex ratio meter. Once this phase information is in hand, the calibration may be effected by use of existing four-port calibration methods. This paper will concern itself primarily with a method for obtaining this reduction from a six-port to a four-port In keeping with its scope, however, only a general statement of the results is possible. The mathematical basis for these will be developed in a paper to follow.

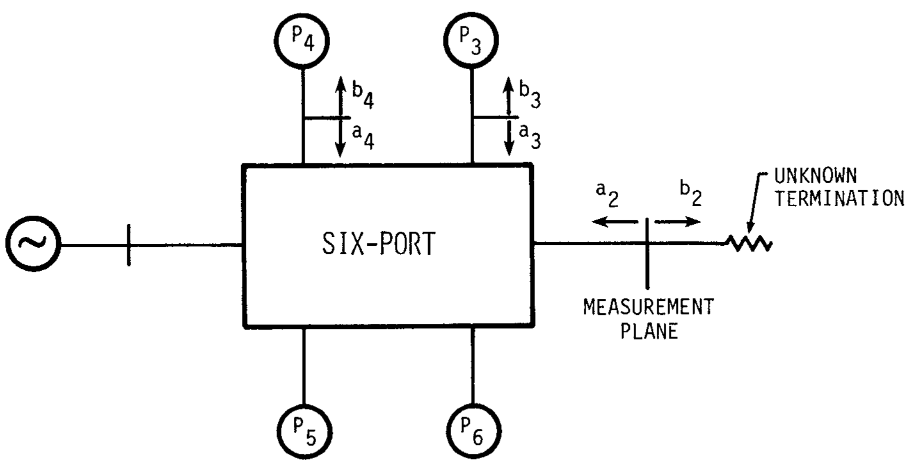

Figure 1. The Six-Port Technique Promises to Have a Major Impact on Future Automatic Network Analyzers

Let P_3, P_4, P_5, P_6 represent the power readings at the respective detectors for the six-port, while b_3, b_4 represent the complex wave amplitudes or voltages at arms 3 and 4. Analytically,

$$\frac{b_3}{b_4} = F\left\{\frac{P_3}{P_4}, \frac{P_5}{P_4}, \frac{P_6}{P_4}, C_1 \ldots C_5\right\} \qquad (1)$$

where $C_1 \ldots C_5$ are five constants whose values are determined by the design of the six-port. The problem is to determine $C_1 \ldots C_5$.

It is convenient to think of $\frac{P_3}{P_4}, \frac{P_5}{P_4}, \frac{P_6}{P_4}$, as representing a point in a 3-dimensional "P-space". As noted in the prior treatment[2] there is a constraining relationship between $\frac{P_3}{P_4}, \frac{P_5}{P_4}$, and $\frac{P_6}{P_4}$. In particular the collection of all possible values for $\frac{P_3}{P_4}, \frac{P_5}{P_4}, \frac{P_6}{P_4}$ lie on a surface in P-space. This surface is a paraboloid of elliptic cross section, moreover it is tangent to the planes $\frac{P_3}{P_4} = 0$, $\frac{P_5}{P_4} = 0$, and $\frac{P_6}{P_4} = 0$.

The general quadric surface involves nine constants. However the foregoing constraints (paraboloid and tangency conditions) reduce the number of parameters from nine to five. The determination of these five parameters $(C_1 \ldots C_5)$ which characterize the surface permit one to specify F and thus effect the reduction from a six-port to a four-port. In principle these five parameters may be found merely by observing the response $\frac{P_3}{P_4}, \frac{P_5}{P_4}, \frac{P_6}{P_4}$ for five arbitrary and unknown terminations and solving a system of five simultaneous equations. Unfortunately, however, these equations are of third degree, and unless a fairly good estimate of the desired solution is in hand, the well-known numerical methods for handling this problem are at best lengthy, and may fail to converge to the desired root. (It was for these reasons that the earlier solution[2] was only marginally satisfactory).

One method of obtaining an initial estimate of the solution is to observe the responses $\frac{P_3}{P_4}, \frac{P_5}{P_4}, \frac{P_6}{P_4}$ for nine rather than five unknown terminations. One can then obtain the equation of a general quadric surface through these points by solving a linear system of nine equations and unknowns. Ideally, this surface would be the paraboloid of interest but because of measurement error, the paraboloid and tangency requirements will only be approximately satisfied. This solution, however, does yield a good starting point for the procedure outlined in the preceding paragraph.

Although this approach is perfectly feasible and, as described in a companion paper[3], has been applied to the dual six-port, a somewhat different procedure for obtaining the initial estimate appears preferable in the immediate context.

As noted in an earlier paragraph, if the six-port is to prove competitive with the four-port method, it is desirable to keep the additional operator effort to a minimum. One of the more attractive four-port calibration methods[4] calls for observing the system response to a single impedance standard and to three positions each of a sliding load and a sliding short. If the number of sliding short positions are increased from three to five, an alternative closed form solution for the paraboloid parameters is possible, but which, because of its length, will be presented in the paper to follow.

Although it may be observed that the five short positons, three load positions and impedance standard represent a total of nine terminations, and thus in principle permit a solution as outlined earlier, the point here is that unless further stipulations are made, the resultant system of nine equations would frequently be ill-conditioned. This problem is avoided by the closed form solution referred to in the preceding paragraph.

This scheme is in current use at NBS in conjunction with power and reflection coefficient type measurements.

Summary

In keeping with its scope, this paper has outlined an approach to the six-port calibration problem which makes it possible to utilize existing four-port procedures.

References

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4. I. Kasa, "Closed-form Mathematical Solutions to Some Network Analyzer Calibration Equations," IEEE Trans. Instrum. & Meas., vol. IM-23, pp 399-402, Dec. 1974.