COMPUTER-AIDED MICROWAVE IMPEDANCE MEASUREMENTS

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The development of better microwave components has made it possible to design more sophisticated systems in the last decade. Great strides have also been made in creating new and better microwave semiconductor devices. In order to adequately characterize these new components and systems, accurate impedance measurements are required at many frequencies. Several manufacturers have recently introduced network analyzers which are capable of providing magnitude and phase information which can be read directly from panel meters. External connectors are provided for analog-to-digital conversion of the data. While these network analyzers are convenient to use, their accuracy is often not as high as desired due to impairment by system imperfections such as coupler directivity and reflections from small discontinuities.

This paper discusses the use of a general purpose digital computer to remove the system errors from microwave impedance measurements while the measured data are being converted to a variety of forms useful for circuit design or device evaluation. Error reduction is accomplished by using the known values and the measured values of three reference impedances to form a matrix. The corrected impedance can then be found from the measured impedance by the use of matrix algebra.

The Z-matrix was selected because appropriate equations[1] are readily available which allow the matrix elements to be determined with any three general reference impedances, provided their values are sufficiently different from each other. An ideal short circuit, ideal open circuit, and a perfectly matched termination could be used if available; however, they would not improve the accuracy.

With the matrix elements determined, the corrected impedance (Z_R) is found from the measured impedance value (Z_S) by use of the relation

$$Z_R = \frac{Z_{12}^2}{Z_{11}-Z_S} - Z_{22} \qquad (1)$$

In order to accommodate measured data from a variety of sources, the computer program was written with several input modes. Mode 1 accepts the return gain (negative return loss)

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in decibels and the angle of the reflection coefficient; mode 2 uses the real and imaginary components of the reflection coefficient and mode 3 uses the magnitude and angle of the reflection coefficient. The output parameters are: frequency, return loss, mismatch loss, standing-wave ratio (as a ratio and in decibels), reflection coefficient (polar form), impedance (polar and rectangular forms), conductance, susceptance, and the capacitance or inductance of an equivalent series impedance. A short-form printout containing only the magnitude and angle of the reflection coefficient can be obtained at the user's option.

The General Radio Type 900 coaxial components listed in column 1 of Table I were used as reference impedances and unknown loads to obtain experimental data. Complete descriptions of the components can be found in the manufacturer's catalog. WNC + LZ5 represents a 5-cm precision 50-ohm air transmission line terminated by a WNC short. The nominal magnitude of the reflection coefficient for the short (P_N) is specified by the manufacturer as greater than 0.9990. Losses in the precision air lines are neglected. Phase angles (ϕ_C) calculated from the lengths of the short circuited lines are given in column 3. Nominal SWR values are given for the calibrated mismatches and the matched termination in column 4 and the SWR values specified on the manufacturer's calibration charts are given along with the corresponding reflection magnitudes in columns 5 and 6. Phase information was not measured by the manufacturer for these loads.

The WNC short circuit and the LZ5 and LZ10 precision lines terminated with the WNC short circuit were used as reference impedances and all of the loads listed in column 1 of Table II were measured 10 times using a Hewlett-Packard 8410A Network Analyzer with an 8414A polar display plug-in. An integrating digital voltmeter was used to read the measured data from the "horizontal" and "vertical" output connectors. The RF signal source was phase-locked to a crystal controlled oscillator. Mode 2 of the computer program was used to correct and average the data; hence, a subscript 2 is used to designate the output data given in Table II. The probable error vectors (P_{E2}) given in column 4 were found from

$$P_E = \frac{1}{C_N}\sqrt{\frac{\sum_{i=1}^{N} (H_A-H_i)^2 + \sum_{i=1}^{N} (V_A-V_i)^2}{N-1}} \qquad (2)$$

where H_i and V_i are rectangular components of the individual complex reflection coefficients; H_A and V_A are average values of H_i and V_i, respectively; N is the number of tests and C_N is a correction factor for small N. The meaning of the error vector and the repeatability of measurements are illustrated in Figure 1 for the WR110 calibrated mismatch. The corrected angles are compared with the calculated angles in column 5 of Table II. The reflection magnitudes for the calibrated mismatch and the termination are compared with calibration measurements made by the General Radio Company using a precision slotted-line in column 6. Comparing the data of Table II with the specifications of Table I shows good agreement in all cases except for the W50 termination which had a magnitude which was too small and a relatively large error vector.

Reducing the data of Table II without correction (mode 5) gave an average value for P_5-P_2 of -0.0016 with an RMS difference of 0.0095 and a standard deviation (σ) of 0.0101. The average difference between corrected and uncorrected angles for the short circuits and the open circuit was -2.73 degrees with $\Delta\phi$ rms = 3.28 degrees and σ = 2.10 degrees. The WR150, WR120 and WR110 mismatches had angular differences of -8.56, -14.63 and -22.8 degrees, respectively. Comparable data were obtained using modes 1 and 4 (mode 1 without correction) to reduce data.

An automatic network analyzer[2] was recently marketed by the Hewlett-Packard Company. This system has an internal computer to control the measurements and to correct the data and reduce it to the desired forms. The S-matrix is used for error corrections and the reference impedances are a short circuit, a short circuited quarter-wave transmission line and a perfectly matched termination which is approximated by using a precision transmission line with a sliding load. Measurements are made with the load in four different positions, thus six measurements are made to calibrate the system at each frequency. This causes no problem with this system since the frequency is stepped automatically under computer control. On the other hand, when measurements must be made manually, doubling the number of required calibration measurements would be a serious handicap. The inherent accuracy should be the same for the method being described and the one used by the automatic system. In order to obtain a comparison, the loads used for the previous tests were measured on an automatic network analyzer. The reflection coefficients are given in columns 2 and 3 of Table III. The angles are compared with the calculated angles in column 4 and magnitudes and angles are compared with mode 2 measurements in columns 5 and 6. The mode 2 measurements agree more closely with the calculated values for the unity reflection loads than do the automatic system measurements. The two methods agree well with each other for the calibrated mismatches. The automatic system measurement for the matched termination is much closer to the General Radio calibration value than the mode 2 measurement is.

The mode 2 measurements used three reference impedances with unity reflection coefficients while the automatic system used two unity reflection references and one reference with near zero reflection. This suggests that at least one reference impedance should have a value close to the value of the unknown impedance. The precision air lines were terminated with a matched load and used to simulate the sliding load used by the automatic system. When the composite "perfect termination" thus formed was used as one reference impedance along with the WNC and the WO and the data were corrected using mode 2, the W50 termination had a reflection coefficient of 0.0027 at -1.64 degrees. The magnitude and angle were in good agreement with the automatic network analyzer values.

The GR-type 900 components were used to demonstrate the capability of the system only because they were conveniently available and precisely characterized. Measurements are not constrained to any particular coaxial line geometry.

The use of a Z-matrix in a computer program makes it possible to greatly reduce measurement errors while requiring a minimum number of calibration measurements. To measure impedances with large reflection coefficients, including values greater than unity, all three reference impedances should have unity reflection coefficients. When reflection coefficients of less than 0.05 are to be accurately measured, one of the reference impedances should be a sliding load in a precision air line. Extra calibration measurements are required when this method is used. Intermediate values of reflection coefficients can be measured accurately with either set of reference impedances, or with other possible combinations.

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References

1. S. Ramo, J. R. Whinnery and T. Van Duzer, Fields and Waves in Communication Electronics, New York: John Wiley & Sons, Inc., 1965, p. 595.
2. Richard A. Hackborn, "An Automatic Network Analyzer System", Microwave Journal, Vol. 11, No. 5, pp. 45-52, May 1968.

TABLE I

SPECIFICATIONS FOR COMPONENTS USED AS LOADS AND REFERENCES AT 5.0000GHz

GR Type 900 Loads	P_N	ϕ_c (degrees)	Nominal SWR	GR Calibration SWR	GR Calibration P_{GR}
WNC	0.999+	180.00			
WNC + LZ5	0.999+	-60.054			
WNC + LZ6	0.999+	179.98			
WNC + LZ7H	0.999+	-0.022			
WNC + LZ10	0.999+	60.011			
WO	0.999+	-31.622			
WNE	0.999+	148.378			
WR150	0.2000		1.5	1.500	0.2000
WR120	0.0909		1.2	1.210	0.0950
WR110	0.0476		1.1	1.125	0.0588
W50	0.0000		1.0	1.0075	0.0037

TABLE II

AVERAGES OF 10 RUNS USING MODE 2 TO CORRECT DATA

*CALIBRATION REFERENCES: WNC, WNC + LZ5, WNC + LZ10

GR Type 900 Loads	P_2	ϕ_2 (degrees)	P_{E2}	$\phi_2-\phi_c$	P_2-P_{GR}
WNC + LZ5*	0.9990	-60.054	0.0000	0.00	
WNC + LZ6	0.9942	179.38	0.0028	-0.60	
WNC + LZ7H	0.9964	0.33	0.0040	0.35	
WNC + LZ10*	0.9990	60.011	0.0000	0.00	
WO	1.0009	-31.49	0.0031	0.13	
WNE	1.0006	148.63	0.0065	0.25	
WR150	0.2036	51.41	0.0020	-	0.0036
WR120	0.0993	52.47	0.0019	-	0.0043
WR110	0.0596	57.08	0.0017	-	0.0008
W50	0.0014	75.56	0.0021	-	-0.0023

TABLE III

HEWLETT-PACKARD AUTOMATIC NETWORK ANALYZER MEASUREMENTS

GR Type 900 Loads	P_{hp}	ϕ_{hp} (degrees)	$\phi_{hp}-\phi_c$	P_2-P_{hp}	$\phi_2-\phi_{hp}$
WNC + LZ5	1.0403	-60.0	0.05	-0.0513	-0.05
WNC + LZ6	0.9975	177.8	-2.18	-0.0033	1.58
WNC + LZ7H	1.0167	0.0	0.022	-0.0203	0.33
WNC + LZ10	0.9853	59.1	-0.91	0.0137	0.91
WO	1.0430	-29.0	2.62	-0.0421	-2.49
WNC	0.9937	149.2	0.82	0.0069	-0.57
WR150	0.2028	50.7		0.0008	0.71
WR120	0.0995	52.6		-0.0002	-0.13
WR110	0.0603	56.4		-0.0007	0.68
W50	0.0023	1.7		-0.0009	73.86

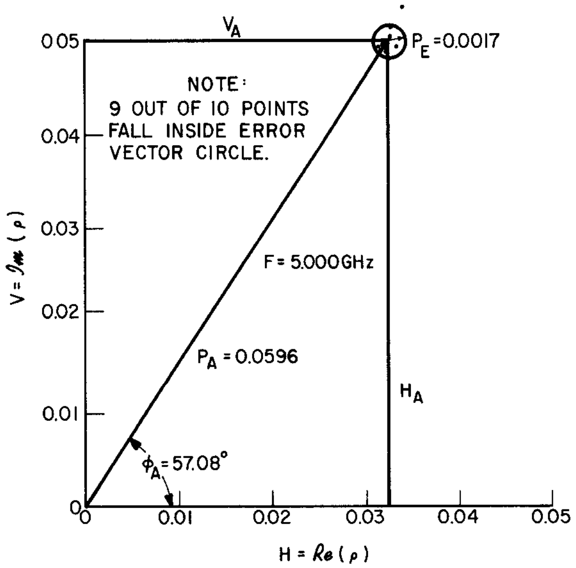

Figure 1 **Repeatability of reflection coefficient measurements with a GR WR110 Mismatch.**