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DEPARTEMENT DE GENIE ELECTRIQUE

CALIBRATION AND MEASUREMENT OF SIX-PORT REFLECTOMETER USING A MATRIX APPROACH
PART I - THEORY

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ABSTRACT

A new method based on matrix representation of a six-port is used to relate the four power readings to the reflection coefficient. The advantages of this method are related to the fact that no specific port is required to set a reference power level and the linearity of the related equations facilitate numerical processing and greatly reduce the calculation time such that real time measurements can be made.

I INTRODUCTION

The six-port reflectometer technique introduced mainly by Engen and Hoer provides an automatic method for measuring complex reflection coefficients of one port microwave junction via power measurements only. Since its introduction a substantial literature has been developed dealing with theoretical and practical aspects of the method [1-8]. Many authors tried to use projective geometry concepts to describe the relationship between power levels and the reflection coefficient [9-11]. In this paper a new approach to the calibration of the six-port reflectometer, and the measurement of reflection coefficients is described, using a matrix concept. Noteworthy in this technique is the absence of the need for selecting a preferred normalizing port, and an explicit solution is obtained using only linear equation techniques. This approach make it possible to calculate the reflection coefficient from power readings quickly; real time measurement of S parameters can be made.

II ANALYSIS OF AN ARBITRARY MICROWAVE NETWORK

Considering an arbitrary microwave network with n ports ($n \geq 6$) (Fig. 1). A reference signal is introduced at port 1, an unknown signal of the same frequency at port 2, ports 3,...n are terminated with power detectors. Referring to Fig. 1, the N ports network can be characterized by its internal scattering coefficients as follows:

$$b_j = \sum_{i=1}^{2} s_{ji}a_i + \sum_{i=3}^{n} s_{ji}a_i \qquad \text{for} \qquad j=1,2 \qquad (1)$$

$$b_e = \sum_{i=1}^{2} s_{ei}a_i + \sum_{i=3}^{n} s_{ei}a_i \qquad \text{for} \qquad e=3,\ldots n \qquad (2)$$

With the reflection coefficient of the power detector itself is D_e,we then have:

$$a_e = D_e b_e \; ; \qquad e = 3,\ldots n \qquad (3)$$

Referring to equation (3), equation (2) becomes

$$b_e = \sum_{i=1}^{2} s_{ei}a_i + \sum_{i=3}^{n} s_{ei}D_i b_i \qquad \text{for} \qquad e=3,\ldots n$$

From (1), the outgoing amplitude b_2 is :

$$b_2 = s_{21}a_1 + s_{22}a_2 + \sum_{i=3}^{n} s_{2i}\, a_i \qquad (4)$$

and therefore

$$a_1 = \frac{1}{s_{21}} [b_2 - s_{22}a_2 - \sum_{i=3}^{n} s_{2i}D_i b_i] \qquad (5)$$

Substituting (3) and (5) into (2) gives

$$b_e = s_{e1}\frac{1}{s_{21}} \cdot [b_2 - s_{22}a_2 - \sum_{i=3}^{n} s_{2i}D_i b_i] + s_{e2}a_2 + \sum_{i=3}^{n} s_{ei}D_i b_i \qquad (6)$$

for $e = 3,\ldots n$

and

$s_{21} = 0$

The power detected is proportional to the square of $|b_e|$, so we can write

$$P_e = K\,|b_e|^2 = K\, b_e b_e^* \; , \quad \text{for} \quad e = 3,\ldots n \qquad (7)$$

Ideal power detector: ($D_e = 0$)

In this case, the outgoing amplitude b_e ($e = 3,...n$) vanishes

$D_e = 0$ for $e = 3,...n$

Consequently, equation (6) becomes

$$b_e = \frac{s_{e1}}{s_{21}} [b_2 - s_{22}a_2] + s_{e2}a_2$$

therefore

$$b_e = \frac{s_{e1}}{s_{21}} b_2 + (s_{e2} - \frac{s_{e1}s_{22}}{s_{21}})a_2 \quad , \quad \text{for} \quad e = 3,...n \qquad (8)$$

and the detected power level becomes

$$p_e = K [\frac{s_{e1}}{s_{21}} b_2 + (s_{e2} - \frac{s_{e1}s_{22}}{s_{21}})a_2] [\frac{s_{e1}}{s_{21}} b_2 + (s_{e2} - \frac{s_{e1}s_{22}}{s_{21}})a_2]^* \qquad (9)$$

for $e = 3,...n$

Ideal matched network ($s_{ii} = 0$)

In this case, we suppose that all ports are matched, hence, we can write:

$s_{ii} = 0$ for $i = 1,...n$

so, the power detected will be

$$p_e = K [\frac{s_{e1}}{s_{21}} b_2 + s_{e2}a_2] [\frac{s_{e1}}{s_{21}} b_2 + s_{e2}a_2]^* \qquad (10)$$

for $e = 3,...n$

In the coming treatment we don't need to state the above assumption ($s_{ii} = 0$). However equation (8) is equivalent to

$$b_e = M_e a_2 + N_e b_2 \qquad e = 3,...n \qquad (11)$$

where

$$M_e = s_{e2} - \frac{s_{e1}s_{22}}{s_{21}} \quad , \quad \text{for} \quad e = 3,...n$$

and

$$N_e = \frac{s_{e1}}{s_{21}} \quad , \qquad \text{for} \quad e = 3,...n$$

For an arbitrary six-port junction and non ideal power detectors ($D_i \neq 0$) it can be shown that equation (11) still valid with different coefficients M'_e and N'_e.

The reflection coefficient of the device under test is

$$\Gamma = \frac{a_2}{b_2} \qquad (12)$$

Substituting (12) into (11) gives

$$b_e = b_2 M_e [\Gamma + \frac{N_e}{M_e}] \qquad \text{for} \qquad e = 3,...n \qquad (13)$$

Substituting (13) into (7) gives

$$p_e = K|b_2|^2|M_e|^2 \; [\Gamma + \frac{N_e}{M_e}] \; [\Gamma + \frac{N_e}{M_e}]^*$$

or

$$p_e = K|b_2|^2|M_e|^2 \; [\; \Gamma^2 + (\frac{N_e}{M_e})^2 + \Gamma \frac{N_e^*}{M_e^*} + \Gamma^* \frac{N_e}{M_e} \;] \qquad (14)$$

$$\text{for} \quad e = 3,....n$$

Equation (14) can be represented as a scalar products of 2 vectors, such that:

$$P_e = K|b_2|^2 \quad \underline{M}.\underline{R} \quad , \quad \text{for} \quad e = 3,...n \qquad (15)$$

where

$$\underline{M} = \begin{vmatrix} |N_e|^2 \\ |M_e|^2 \\ N_e^* M_e \\ N_e M_e^* \end{vmatrix} \qquad \text{and} \qquad \underline{R} = \begin{vmatrix} 1 \\ |\Gamma|^2 \\ \Gamma \\ \Gamma^* \end{vmatrix}$$

III Reflection Measurements using a six-port

In the case of a six-port network (n=6), we have 4 power output levels defining a power vector, such

$$\underline{P} = \begin{vmatrix} P_3 \\ P_4 \\ P_5 \\ P_6 \end{vmatrix}$$

This power vector can be related to the reflection coefficient vector $\underline{R}$ by a 4x4 matrix M as follows:

$$\begin{vmatrix} P_3 \\ P_4 \\ P_5 \\ P_6 \end{vmatrix} = K|b_2|^2 \begin{vmatrix} |N_3|^2 & |M_3|^2 & N_3^*M_3 & N_3M_3^* \\ |N_4|^2 & |M_4|^2 & N_4^*M_4 & N_4M_4^* \\ |N_5|^2 & |M_5|^2 & N_5^*M_5 & N_5M_5^* \\ |N_6|^2 & |M_6|^2 & N_6^*M_6 & N_6M_6^* \end{vmatrix} \begin{vmatrix} 1 \\ \Gamma\Gamma^* \\ \Gamma \\ \Gamma^* \end{vmatrix}$$

or

$$\underline{P} = K|b_2|^2 \quad M.\underline{R} \tag{16}$$

by introducing the linear operator T as follows:

$$T = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/2 & 1/2 \\ 0 & 0 & j/2 & -j/2 \end{vmatrix}$$

we can relate the reflection coefficient vector $\underline{R}$ to a transformed reflection coefficient vector $\underline{\Gamma}$, such that

$\underline{\Gamma} = T.\underline{R}$ or $R = T^{-1}\underline{\Gamma}$

where

$$\underline{\Gamma} = \begin{vmatrix} 1 \\ \Gamma\Gamma^* = |\Gamma|^2 \\ R_e(\Gamma) \\ I_m(\Gamma) \end{vmatrix}$$

The power vector can now be related to the transformed reflection coefficient as follows:

$$\underline{P} = K\,|b_2|^2\; M.T^{-1}\,\underline{\Gamma}$$

$$\underline{P} = K\,|b_2|^2\; C\;\underline{\Gamma} \qquad (18)$$

where $C = M.T^{-1}$

The matrix C is a real matrix (see Appendix A) and represents the invariant properties of the measurement instrument, including the six-port network, and $K|b_2|^2$ is the power level at the input of the device under test.

Referring to (18), the transformed reflection coefficient can also be expressed as follows:

$$\underline{\Gamma} = \frac{1}{K|b_2|^2}\; C^{-1}\,\underline{P} = \frac{1}{K|b_2|^2}\; X\,\underline{P}\,.$$

where $C^{-1} = X$ is the inverse matrix of C

Matrix C is determined by the circuit design of the 6 port junction; it is therefore necessary that the design of the six-port be such that this matrix is non-singular (see Appendix C).

If we denote X_i the i^{th} row of Matrix X, we can get from (18):

$$1 = \frac{1}{K|b_2|^2}\; X_1.P \quad \text{or} \quad K|b_2|^2 = X_1.P \qquad (a)$$

$$|\Gamma|^2 = \frac{1}{K|b_2|^2}\; X_2.P \quad \text{or} \quad |\Gamma|^2 = \frac{X_2.P}{X_1.P} \qquad (b) \qquad (20)$$

$$R_e(\Gamma) = \frac{1}{K|b_2|^2}\; X_3.P \quad \text{or} \quad R_e(\Gamma) = \frac{X_3.P}{X_1.P} \qquad (c)$$

$$I_m(\Gamma) = \frac{1}{K|b_2|^2}\; X_4.P \quad \text{or} \quad I_m(\Gamma) = \frac{X_4.P}{X_1.P} \qquad (d)$$

It is important to note that equation 20(a) determines the unknown power level $K|b_2|^2$ found in the denominator of equations 20(b), (c) and (d). This feature dispenses the need to use a specific power port to normalize the power levels from the remaining ports.

IV <u>Calibration technique for the six-port</u>

To calibrate a six-port in a given frequency band it is necessary to determine the matrix X at a number of pre-determined frequency points within the chosen bandwidth.

The determination of matrix X (16 unknowns) needs to be resolved in a linear system with 16 equations. If any one element of the matrix C can be fixed, five calibration standards are required to solve the 15 equations, in order to determine the remaining 15 elements of C. In fact, the matrix X can be found just by inverting the matrix C (we assume that $C_{11}=1$). The known reflection coefficient $\underline{\Gamma}_s$ for each standard can be related to the power vector $\underline{P}_s$ and the unknown calibration matrix X as follows:

$$\underline{\Gamma}_s = \frac{1}{K|b_2|^2} X \cdot \underline{P}_s \qquad (21)$$

V <u>Measurement of the reflection coefficient</u>

The determination of the complex reflection coefficient from the four power readings is determined using equation (20), with the calibration matrix X at each frequency point.

Real time measurements can be made because the required calibrations are simply and rapidly performed with a 32-bit micro-computer.

In Appendix B it is shown that the value of the reflection coefficient corresponds to the intersection of four circles in the Γ plane where the values of the radius of each circle is proportional to the square root of the power reading.

In Appendix C it is shown that the center of each circle is determined by the six-port design, and the calibration matrix elements are directly related to the position of the four circles in the Γ plane.

A six-port network analyzer system controlled with a HP 9816 desk-top computer has been assembled and operated with a software using this matrix approach. Experimental results will be described in Part II of this paper.

Conclusion

A new matrix approach has been proposed for six-port calibration and measurement. The technique developed has the following virtues:

i) The calibration of the six-port needs five known standards only.

ii) Only linear techniques are used to calibrate the six-port junction and to measure the reflection coefficient.

iii) The need to identify one port as a normalizing port is not necessary.

iv) the calculation of reflection coefficient from the power readings can be done quickly enough to support real time measurements.

Appendix A

Proof that Matrix C is real matrix

C Matrix is the product of $M.T^{-1}$

where.

$$T^{-1} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/2 & 1/2 \\ 0 & 0 & j/2 & -j/2 \end{vmatrix}^{-1} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & j \\ 0 & 0 & 1 & -j \end{vmatrix}$$

The Matrix M can be presented as:

$$M = \begin{vmatrix} |N_3|^2 & |M_3|^2 & N_3^* M_3 & N_3 M_3^* \\ |N_4|^2 & |M_4|^2 & N_4^* M_4 & N_4 M_4^* \\ |N_5|^2 & |M_5|^2 & N_5^* M_5 & N_5 M_5^* \\ |N_6|^2 & |M_6|^2 & N_6^* M_6 & N_6 M_6^* \end{vmatrix}$$

By normalizing all the elements of each row of M matrix by the second we get

$$M = \mathrm{Diag}\,(|M_3|^2\ ,\ |M_4|^2\ ,\ |M_5|^2\ ,\ |M_6|^2).M'$$

where

$$M' = \begin{vmatrix} \left|\frac{N_3}{M_3}\right|^2 & 1 & \left|\frac{N_3^*}{M_3^*}\right| & \left|\frac{N_3}{M_3}\right| \\ \left|\frac{N_4}{M_4}\right|^2 & 1 & \left|\frac{N_4^*}{M_4^*}\right| & \left|\frac{N_4}{M_4}\right| \\ \left|\frac{N_5}{M_5}\right|^2 & 1 & \left|\frac{N_5^*}{M_5^*}\right| & \left|\frac{N_5}{M_5}\right| \\ \left|\frac{N_6}{M_6}\right|^2 & 1 & \left|\frac{N_6^*}{M_6^*}\right| & \left|\frac{N_6}{M_6}\right| \end{vmatrix}$$

Consequently, one can get:

$$C = MT^{-1} = \mathrm{Diag}(|M_3|^2,\ |M_4|^2,\ |M_5|^2,\ |M_6|^2) \bullet M' \bullet T^{-1}$$

where $T^{-1} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & j \\ 0 & 0 & 1 & -j \end{vmatrix}$.

finally, we get

$$C = \mathrm{Diag}(|M_3|^2, |M_4|^2, |M_5|^2, |M_6|^2) . \begin{vmatrix} \left|\frac{N_3}{M_3}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_3^*}{M_3^*}\right| & 2\mathrm{Im}\left|\frac{N_3}{M_3}\right| \\ \left|\frac{N_4}{M_4}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_4^*}{M_4^*}\right| & 2\mathrm{Im}\left|\frac{N_4}{M_4}\right| \\ \left|\frac{N_5}{M_5}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_5^*}{M_5^*}\right| & 2\mathrm{Im}\left|\frac{N_5}{M_5}\right| \\ \left|\frac{N_6}{M_6}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_6^*}{M_6^*}\right| & 2\mathrm{Im}\left|\frac{N_6}{M_6}\right| \end{vmatrix}$$

We conclude that Matric C is a real matrix.

Appendix B

As we have shown in Appendix A, the power detected can be represented by:

$$P_e = |M_e|^2 K|b_2|^2 \left[\left|\frac{N_e}{M_e}\right|^2 + |\Gamma|^2 + 2\mathrm{Re}\left(\frac{N_e}{M_e}\right) \mathrm{Re}(\Gamma) + 2\mathrm{Im}\left(\frac{N_e}{M_e}\right) \mathrm{Im}(\Gamma) \right]$$

or also by:

$$P_e = |M_e|^2 K|b_2|^2 \{[\mathrm{Re}(\Gamma) + \mathrm{Re}(N_e/M_e)]^2 + [\mathrm{Im}(\Gamma) + \mathrm{Im}(N_e/M_e)]^2\} \quad \text{(B-1)}$$

The last equation is the equation of a circle in the Γ plane. In the case of the six-port, the solution is the intersection of four circles as illustrated in Fig. 2, where

$$C_3 \left| \begin{array}{l} -\mathrm{Re}(\frac{N_3}{M_3}) \\ -\mathrm{Im}(\frac{N_3}{M_3}) \end{array} \right. ; \quad C_4 \left| \begin{array}{l} -\mathrm{Re}(\frac{N_4}{M_4}) \\ -\mathrm{Im}(\frac{N_4}{M_4}) \end{array} \right. ; \quad C_5 \left| \begin{array}{l} -\mathrm{Re}(\frac{N_5}{M_5}) \\ -\mathrm{Im}(\frac{N_5}{M_5}) \end{array} \right. ;$$

$$C_6 \left| \begin{array}{l} -\mathrm{Re}(\frac{N_6}{M_6}) \\ -\mathrm{Im}(\frac{N_6}{M_6}) \end{array} \right. \quad \text{(B-1)}$$

$$R_3 = \left| \frac{P_3}{K|b_2|^2 \; |M_3|^2} \right|^{\frac{1}{2}} \quad \text{(B-2)}$$

$$R_4 = \left| \frac{P_4}{K|b_2|^2 \; |M_4|^2} \right|^{\frac{1}{2}} ; \quad R_5 = \left| \frac{P_5}{K|b_2|^2 \; |M_5|^2} \right|^{\frac{1}{2}} ; \quad R_6 = \left| \frac{P_6}{K|b_2|^2 \; |M_6|^2} \right|^{\frac{1}{2}}$$

C_i, R_i are the center and the radius of i^{th} circle respectively.

The choice of the circle centers C_3, C_4, C_5 and C_6 can be used as a means to optimize the design of the six-port (see Appendix C).

Appendix C

Relationship between calibration Matrix and the configuration of the six-port

In Appendix A it is shown that the Matrix C is real. However the Matrix C can be represented as the product of a diagonal matrix N and a matrix C' such that

$$C = N \bullet C' \qquad (C.1)$$

where

$$N = \mathrm{Diag}(|M_3|^2,\ |M_4|^2,\ |M_5|^2,\ |M_6|^2)$$

and

$$C' = \begin{vmatrix} \left|\frac{N_3}{M_3}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_3^*}{M_3^*}\right| & 2\mathrm{Im}\left|\frac{N_3}{M_3}\right| \\ \left|\frac{N_4}{M_4}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_4^*}{M_4^*}\right| & 2\mathrm{Im}\left|\frac{N_4}{M_4}\right| \\ \left|\frac{N_5}{M_5}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_5^*}{M_5^*}\right| & 2\mathrm{Im}\left|\frac{N_5}{M_5}\right| \\ \left|\frac{N_6}{M_6}\right|^2 & 1 & 2\mathrm{Re}\left|\frac{N_6^*}{M_6^*}\right| & 2\mathrm{Im}\left|\frac{N_6}{M_6}\right| \end{vmatrix}$$

Regarding to Appendix B, the Matrix C' can be related directly to the position of the circle centers in Γ plane, as follows:

$$C' = \begin{vmatrix} R_3^2 & 1 & 2x_3 & 2y_3 \\ R_4^2 & 1 & 2x_4 & 2y_4 \\ R_5^2 & 1 & 2x_5 & 2y_5 \\ R_6^2 & 1 & 2x_6 & 2y_6 \end{vmatrix}$$

where

$$\cdot\ x_i = \mathrm{Re}\left(\frac{N_i}{M_i}\right)$$

$$\cdot\ y_i = \mathrm{Im}\left(\frac{N_i}{M_i}\right)$$

$$\cdot\ R_i = 0C_i$$

$$\cdot\ 0C_i = \begin{vmatrix} -x_i \\ -y_i \end{vmatrix}$$

for $i = 3, 4, 5$ and 6

C' has to be non singular for an acceptable six-port design.

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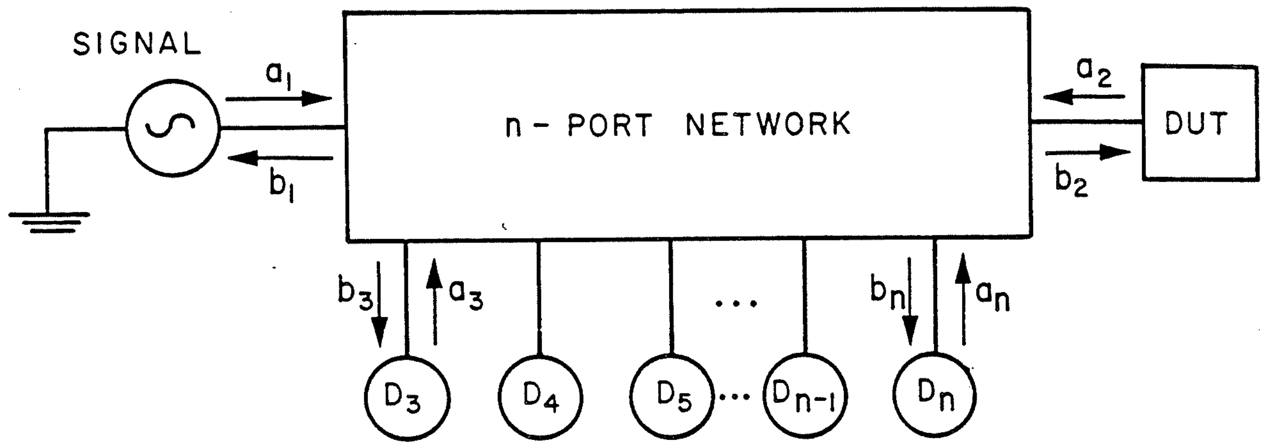
LIST OF FIGURES

FIG. 1 General configuration of n-port network

FIG. 2 Graphical solution in Γ plane



DUT : DEVICE UNDER TEST

D_i : i^{th} POWER DETECTOR

FIGURE 1

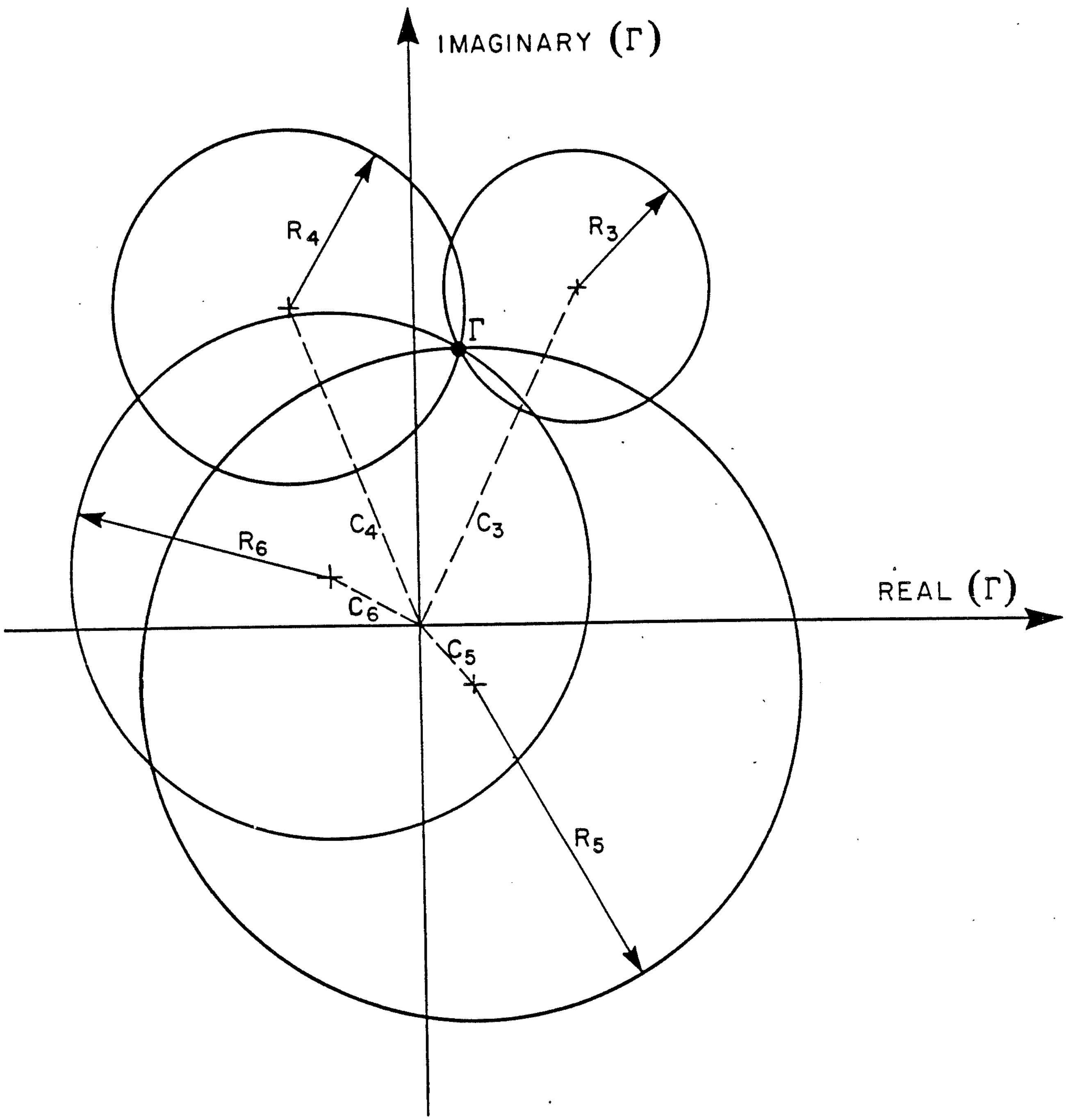


FIGURE 2