Software Developement with Two Port Calibration Techniques for RHIC Impedance Measurements*

Vibha Mane and Tom Shea
Brookhaven National Laboratory, Upton, NY 11973

Abstract

The coupling impedance of accelerator devices is measured by simulating the beam with a central wire and measuring the scattering parameters of the system. The wire pipe system forms a mismatch with the 50 ohm transmission line. An integrated software environment has been developed in LabVIEW, for the Macintosh. The program measures the scattering parameters of some known standards, determines the correct scattering parameters of a device using TRL calibration technique and gives the impedance of the device. Its performance has been tested for some known microwave devices.

I. INTRODUCTION

The Thru-Reflect-Line (TRL) algorithm deembeds the scattering parameters and hence the impedance of a Device Under Test (DUT). A LabVIEW program with user interface is written to implement this algorithm. The program acquires data from HP8753 Network Analyzer via GPIB bus, or reads it from a file, and obtains the impedance of a device placed between mismatched ports. The algorithm is reproduced here [1],[2]; and the implementation is described in detail.

The nonideal port at each end of the two-port DUT is modeled by an ideal port in cascade with an error box [Figure 1]. The scattering parameters are measured for three known conditions between the measurement planes M1 and M2, using the Network Analyzer. The scattering parameters of the Error Boxes A and B are then determined, and the scattering parameter and the impedance of the DUT is calculated.

II. SCATTERING PARAMETERS AND IMPEDANCE

The scattering parameters of a microwave network give the relationship between the incident waves and the reflected waves at its terminals[3].

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

a_1, a_2 are the incident waves; b_1, b_2 are the reflected waves;

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \text{ is the Scattering Matrix}$$

Also defined is the transmission matrix which gives the relationship between the input quantities and the output quantities. This is useful when two ports are connected in cascade, because the transmission matrix of the cascaded ports is equal to the product of the transmission matrix of each port.

$$\begin{bmatrix} b_2 \\ a_2 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} b_1 \\ a_1 \end{bmatrix}$$

$$R = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \text{ is the Transmission matrix}$$

For the measurement of the longitudinal coupling impedance of accelerator devices, the beam is simulated by a current in a wire placed at the axis of the pipe. The longitudinal impedance is given by [4]

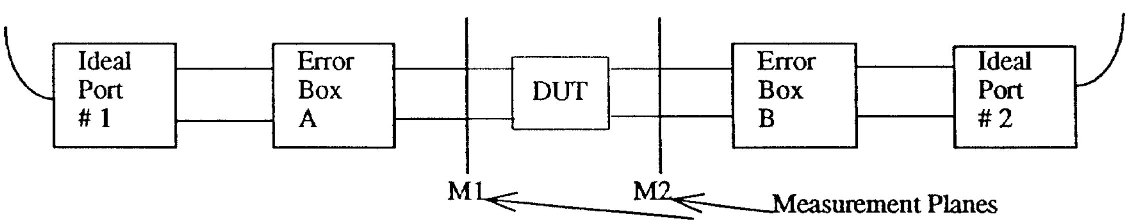

Figure 1. Model for Two Port Calibration, with mismatches represented by error boxes.

* Work supported by the U.S. Department of Energy

$$Z(\omega) = 2Z0\frac{(S_{21}(ref) - S_{21}(DUT))}{S_{21}(DUT)}$$

where S21(ref) is the scattering parameter with DUT replaced by a reference pipe, Z0 is the characteristic impedance of the pipe wire system.

III. PROGRAM ALGORITHM

A. Measurements

The scattering parameters between the measurement planes M1 and M2 are measured for the following four cases:

(i) Thru Measurement: The measurement planes M1 and M2 are connected and all the S parameters are measured.

(ii) Reflect Measurement: A reflective load of unknown reflection coefficient Γ is connected at the measurement plane M1 and S_{11} is measured. The reflective load is connected at measurement plane M2 and S_{22} is measured.

(iii) Line (Delay) Measurement: A nonreflecting transmission line of arbitrary length is connected between M1 and M2 and the S parameters are measured.

(iv) Device Measurement: The device is placed between the measurement planes M1 and M2, and the S parameters are measured.

B. Determining Error Matrices

The transmission matrices R_A and R_B of the error ports A and B are determined as follows:

$$R_T = R_A R_B \tag{1}$$

R_T is the transmission matrix obtained from the thru measurement

$$R_D = R_A R_l R_B \tag{2}$$

R_D is the transmission matrix obtained from the line measurement

$R_l = \begin{bmatrix} e^{-\gamma l} & 0 \\ 0 & e^{\gamma l} \end{bmatrix}$ is the transmission matrix of the nonreflecting delay line.

From (1) and (2)

$$R_M R_A = R_A R_l$$

where $R_M = R_D R_T^{-1} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$

For Port A, write $R_A = \begin{bmatrix} ka & pb \\ k & p \end{bmatrix}$

Solve for a and b,

$$a, b = -\frac{(m_{22} - m_{11})}{2m_{21}} \pm \sqrt{\left(\frac{m_{22} - m_{11}}{2m_{21}}\right)^2 + \frac{m_{12}}{m_{21}}}$$

Select a and b such that $|a| > |b|$.

Similarly for Port B

$$R_B R_N = R_l R_B \text{ where } R_N = R_T^{-1} R_D = \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix}$$

$$R_N^T = \begin{bmatrix} nt_{11} & nt_{12} \\ nt_{21} & nt_{22} \end{bmatrix}$$

$$R_N^T R_B^T = R_B^T R_l^T$$

write $R_B^T = \begin{bmatrix} rc & sd \\ r & s \end{bmatrix}$

Solve for c and d,

$$c, d = -\frac{(nt_{22} - nt_{11})}{2nt_{21}} \pm \sqrt{\left(\frac{nt_{22} - nt_{11}}{2nt_{21}}\right)^2 + \frac{nt_{12}}{nt_{21}}}$$

Select c and d such that $|c| > |d|$.

The reflection coefficient Γ is determined as follows

With Port A connected to the load,

$$p = \pm\sqrt{\frac{\Gamma(a - w_1)}{(a-b)(w_1 - b)}} \tag{3}$$

$w_1 = S_{11}$ when Port A is connected to the reflective load, Γ is the reflection coefficient of the load.

Also for a reciprocal network $|R_A| = 1$ gives

$$k = \frac{1}{p(a-b)} \tag{4}$$

With Port B connected to the load,

$$s = \pm\sqrt{\frac{\Gamma(w_2 + c)}{(c-d)(w_2 + d)}} \tag{5}$$

$w_2 = S_{22}$ when Port B is connected to the reflective load.

For the reciprocal network B, $|R_B| = 1$ gives

$$r = \frac{1}{s(c-d)} \tag{6}$$

From $R_T = R_A R_B$

$$R_T = \begin{bmatrix} karc + pbsd & kar + pbs \\ krc + psd & kr + ps \end{bmatrix}$$

Therefore

$$S_{11T} = \frac{p^2\left(\frac{s}{r}\right)(a-b)b + a}{p^2\left(\frac{s}{r}\right)(a-b) + 1} \tag{7}$$

From equations (3), (5) and (7)

$$\Gamma = \pm\sqrt{\frac{(S_{11T}-a)\ (w1-b)\ (w2+d)}{(S_{11T}-b)\ (w1-a)\ (w2+c)}}$$

After determining Γ, p and s are determined from equations (3) and (5); k and r are determined from (4) and (6). In the Thru-Short-Delay (TSD) algorithm, Γ is set to -1.

The sign of p, k and r, s is selected by comparing the sign of $R_A R_B$ with that of R_T. The sign of Γ is determined by knowing whether the load is closer to a short or an open.

C. Determining the Scattering matrix of the device

$$R_{MDUT} = R_A R_{DUT} R_B$$

R_{MDUT} is the transmission matrix of the measured device. R_{DUT} is the transmission matrix of the calibrated device.

D. Length of delay

The frequencies at which the length of the delay line is an integer multiple of half wavelength, i.e.

$l = \mp n\frac{\lambda}{2}$, both $e^{\gamma l}$ and $e^{-\gamma l} = \pm 1$; $R_M = \mp 1\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$ at these values. Therefore, at these frequencies, measurements from the second delay are used. The length of the second transmission line should not be a multiple of the length of the first transmission line. The difference between the diagonal elements of R_M gives a criteria for switching to the second delay.

IV. EXPERIMENTAL RESULTS

Measurements were done with a 400 MHz filter as a device. The device is connected to the two ports of the Network Analyzer and a large mismatch is placed at Port B. Figure 2 shows the S_{21} parameter of the uncalibrated device. Fig 3 shows the S_{21} parameter of the device obtained from the above calibration algorithm. This matches with S_{21} parameter measured with the Network Analyzer and no mismatches at either Port. The Network Analyzer cannot in general give the desired accuracy, as it requires gating of the mismatches and also requires precision standards (short, open and matching load) which are not easy to construct for a pipe wire system.

The above described software will help measure small impedances, provided the transformer from the 50 ohm cable to the wire pipe geometry gives sufficient transmitted signal. The measurements can be further enhanced using attenuation pads. Results of some measurements using similar algorithm are described in [5].

V. REFERENCES

[1] R. A. Soares, P. Gouzien, P. Legaud and G. Follot, IEEE Trans. Microwave Theory Tech, vol. 37, pp. 1669-1673, Nov 1989.

[2] G. F. Engen and C. A. Hoer, IEEE Trans. Microwave Theory Tech., vol. MTT-27. pp. 987-998, Dec 1979.

[3] S. Ramo, J. Whinnery, John Wiley & Sons, 1956.

[4] H. Hahn, F. Pedersen, BNL 50870, April 1978.

[5] L.S. Walling, D.E. McMurray, D.V. Neuffer, H.A. Thiessen, Nucl. Instr. and Meth in Phys Res. A281 (1989) 433-447.

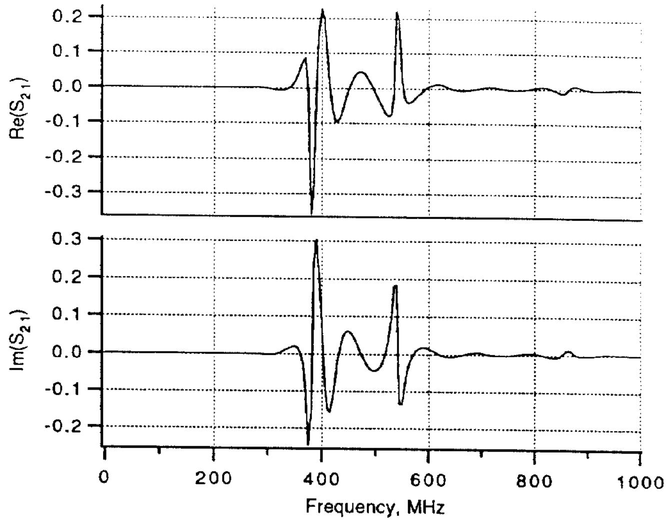

Figure 2. S_{21} Parameter of Uncalibrated Device

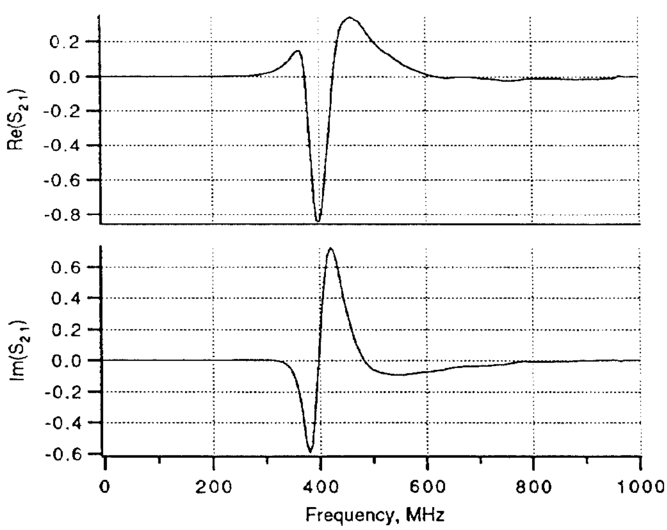

Figure 3. S21 Parameter of Device Calibrated with TRL