TSD versus TRL Calibration and Applications to Beam Impedance Measurements

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Abstract

At FNAL, bench measurements of the longitudinal impedance of various beam line components have been performed using stretched-wire methods. Two network analyzer(NWA) calibration procedures have been implemented and tested in an effort to improve the accuracy of these measurements. The methods, Thru-Short-Delay(TSD) and Thru-Reflect-Line(TRL), each named for their respective calibration standards, are mathematical procedures to extract the S-parameters of a test device from NWA measurements which include the effects of measurement fixtures. The implementation of both these methods has been tested and compared on computer models of the test device and measurement fixtures, whose S-parameters can be exactly computed. The TRL method has been found to be more general and less susceptible to measurement errors. Application of the TRL method to actual stretched-wire impedance measurements has yielded accurate results for a high-Q resonator test device.

1 Introduction

The objective of this work is to recover an equivalent impedance for a given device-under-test(DUT) using a bi-directional reflectometer, otherwise known as a network analyzer(NWA). The basic algorithm consists of applying an incident wave to the DUT, which is characterized as a general two-port network, and measuring the vector voltages scattered into the forward and reverse directions. The resulting data are used to calculate S-parameters. The measurements are complicated by the fact that transitions must necessarily occur between the NWA and the DUT, which are known as launchers, since they represent the elements which effectively launch waves at the DUT. The diagram in Figure 1 is a schematic representation of the measurement setup. Launchers A and B are general, linear networks representing the effect of these transitions, i.e., the errors occuring in the S-parameter measurements of the DUT. The influence of error networks A and B must be calibrated out of the external measurement data in order to accurately evaluate the S-parameters of the DUT. Using standard circuit analysis, it is possible to recover the effective longitudinal impedance of the DUT from the de-embedded S-parameters.

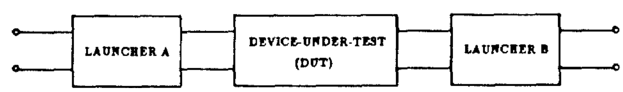

Figure 1: Measurement network

In this work, TOUCHSTONE, an RF/Microwave circuit simulator available from EESof, Inc., is used to simulate an actual DUT with a frequency dependence similar to that expected for a resonant cavity. TOUCHSTONE produces S-parameters for the model cavity, and both the Thru-Short-Delay(TSD)[1] and Thru-Reflect-Line(TRL)[2] de-embedding procedures are employed to recover the model circuit parameters from simulated measurements.

2 Calibration Standards

At FNAL a stretched-wire instrument has been designed to perform bench measurements of the S-parameters of various beam line components. The length of the instrument can be extended easily. Thus, this instrument is appropriate for calibration by the TSD or TRL methods, and so both these methods are implemented at FNAL using FORTRAN codes. The standards required are described below.

THRU(or LINE1) is a length of transmission line with the same characteristic impedance as the DUT

side of A and B. In the simplest case the THRU is a direct connection between A and B.
DELAY(or LINE2) is an identical but longer transmission line. For measurement resolution the difference in length between DELAY(LINE2) and THRU(LINE1) must be less than half a wavelength for the frequency range of interest. Best results are obtained near a quarter wavelength.
SHORT is a perfect short with $S_{11} = S_{22} = -1$ and $S_{12} = S_{21} = 0$.
REFLECT is an unknown reflection (possibly an imperfect short) with no transmission, where $S_{11} = S_{22} = \gamma$ and $S_{12} = S_{21} = 0$.

In order to: (i) Investigate the relative capabilities and restrictions of both methods, and (ii) Test the validity of both FORTRAN codes, the TSD and TRL methods can be applied to computer generated models of the DUT, the launchers and the calibration standards.

3 TOUCHSTONE Model

To accomplish the objectives listed above data files with simulated S-parameter measurements were generated by TOUCHSTONE. These data files contain "measurements" from perfect NWA calibrations using the above standards. Several launcher models with increasing order of complexity were considered. The basic concept was to perform a sensitivity analysis by successively introducing losses and asymmetry in the launcher models and comparing the effect on the simulated TSD and TRL calibrations. Nonideal effects were also introduced in the model calibration standards, shown in Table 1. Line losses and imperfect shorts were investigated in the simulated calibrations.

The most complex of these simulated measurements featured models of the stretched wire launchers with asymmetry. This includes a transition from the 50 ohm coaxial cable input to the stretched wire, which forms a coaxial line with characteristic impedance near 280 ohms. Lumped elements incorporate the change in outer conductor diameter and an estimate of matching resistor parasitics from a previous TOUCHSTONE optimization of a real measurement.

In all of the simulated calibrations the DUT is a model of a cylindrical pillbox cavity with centerwire(TEM mode) plus two modes (850MHz and 1850MHz) relevant to the calibrated frequency range

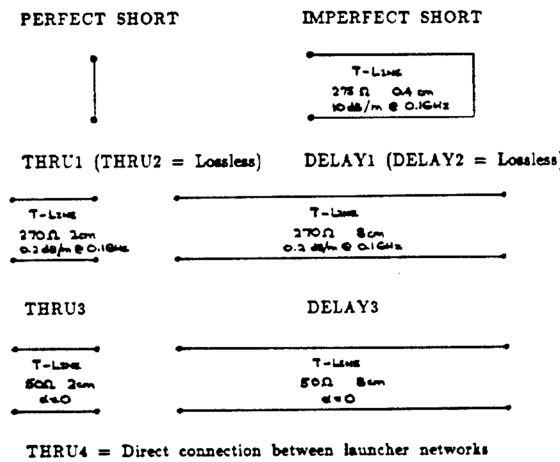

Table 1: Calibration Standards

(400MHz-1200MHz). This device exhibits a shunt resonance at 850MHz.

Using the calibration standards from Table 1, a comprehensive set of TOUCHSTONE data files simulating NWA measurements were generated for the launcher models and DUT described above. The S-parameters for the DUT are known directly from TOUCHSTONE. These can be compared to the de-embedded S-parameters obtained by successively applying the TSD and TRL algorithms to the aforementioned TOUCHSTONE data files.

4 Summary of Results

Results of the simulated calibrations yield the following comparison of TSD versus TRL effectiveness in de-embedding the known S-parameters for the model DUT. Neither method is affected by introducing losses in the launchers, while the TSD method shows noticable performance degradation with the imposition of even minor asymmetry in the launchers. The effects of imposing an imperfect short and simulated losses in the calibration line standards further degrades the performance of the TSD method, whereas the TRL method remains virtually immune and provides accurate results in all cases.

5 TSD vs TRL De-embedding via Cavity Measurements

As a final test, both the TSD and TRL algorithms were applied to data obtained by conducting stretched wire measurements on a RF cavity. In each case, once the S-parameters are extracted, the impedance of the cavity is calculated based on the method described in [2]. Results for the TSD calibration are shown in Figures 2-3, while those for the TRL calibration are shown in Figures 4-5.

The superiority of the TRL method is most easily evident in the phase of the cavity impedance, which shows a linear phase variation with frequency in the TSD case, but is constant, as expected, in the TRL results. This difference is apparently due to the non-ideal lines, which are more realistically taken into account in the TRL algorithm. Such nonideal effects are most important for the measurement of low loss DUT's, such as the RF cavity chosen, especially off resonance.

6 Conclusions

Implementations of the TSD and TRL algorithms have been investigated by a systematic series of tests using artificial data. The TRL calibration method has proven to be the method of choice for stretched wire impedance measurements of beam line devices. This has been confirmed by applying both methods to measurements on a RF cavity.

References

[1] D. McGinnis, "Thru-Short-Delay De-Embedding", internal communication, FNAL, April 1991.

[2] P. Colestock and M. Foley, "A Generalized TRL Algorithm for S-Parameter De-Embedding", FNAL Technical Memo TM-1781, April 1993.

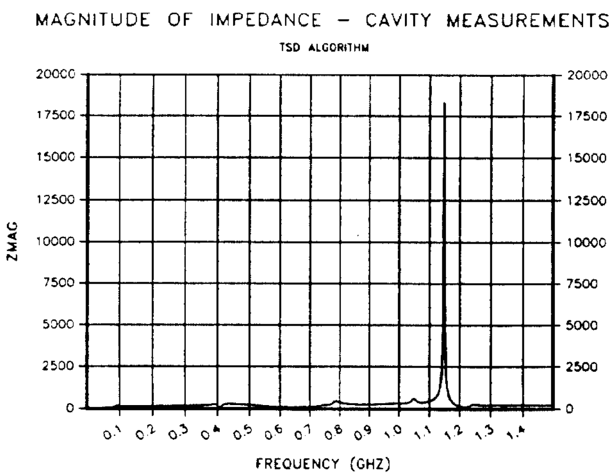

Figure 2

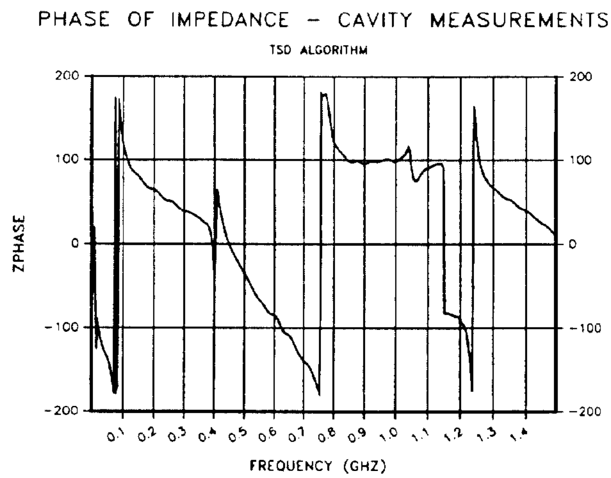

Figure 3

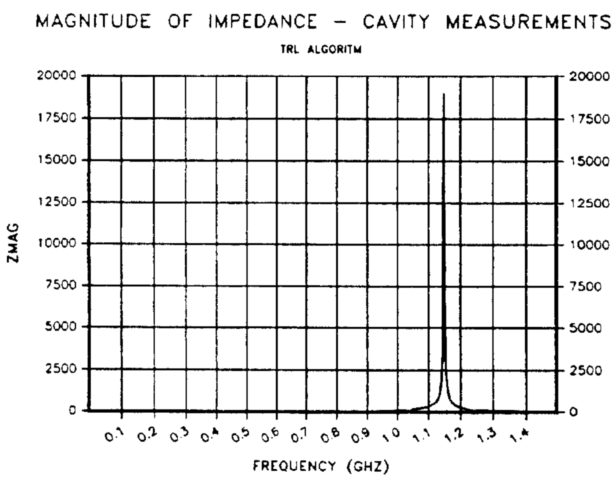

Figure 4

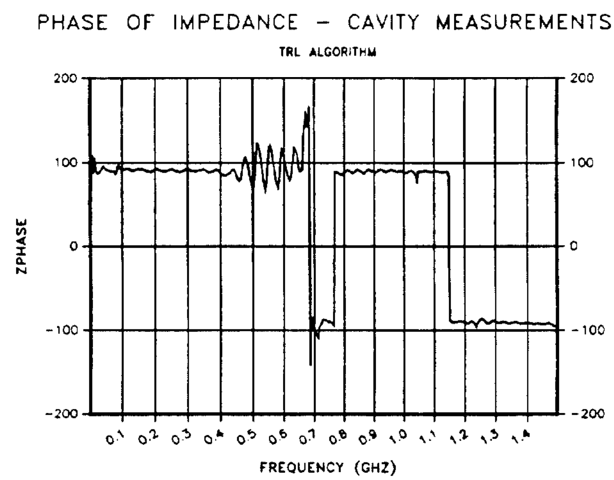

Figure 5