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 occurring 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.

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 trans-
mission 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 im-
perfect short) with no transmission, where \( S_{11} = S_{22} = \gamma \) and \( S_{12} = S_{21} = 0 \).

In order to: (i) Investigate the relative capabili-
ties 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 gen-
erated 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 analy-
sis 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 imper-
fect shorts were investigated in the simulated calibra-
tions.

The most complex of these simulated measure-
ments featured models of the stretched wire launch-
ers 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 incor-
porate the change in outer conductor diameter and an
estimate of matching resistor parasitics from a previ-
ous TOUCHSTONE optimization of a real measure-
ment.

In all of the simulated calibrations the DUT is
a model of a cylindrical pillbox cavity with cen-
terwire (TEM mode) plus two modes (850MHz and
1850MHz) relevant to the calibrated frequency range
(400MHz-1200MHz). This device exhibits a shunt
resonance at 850MHz.

Using the calibration standards from Table 1, a
comprehensive set of TOUCHSTONE data files sim-
ulating 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 ap-
plying the TSD and TRL algorithms to the aforemen-
tioned TOUCHSTONE data files.

4 Summary of Results

Results of the simulated calibrations yield the fol-
lowing comparison of TSD versus TRL effectiveness
in de-embedding the known S-parameters for the
model DUT. Neither method is affected by introduc-
ing losses in the launchers, while the TSD method
shows noticeable performance degradation with the
imposition of even minor asymmetry in the launch-
ers. The effects of imposing an imperfect short and
simulated losses in the calibration line standards fur-
ther 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 algo-
rithms were applied to data obtained by conduc-
ting 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
