Longitudinal Coupling Impedance of a Bellows and a Ceramic Gap in a Circular Beam Pipe for the Advanced Photon Source *

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Abstract

Longitudinal beam coupling impedances of a bellows and a ceramic gap in a circular beam pipe were measured using a TSD/TRL/LRL calibration. The calibration was implemented on a 486PC running LabWindows. The formulae for error matrix determination and measured S-parameter de-embedding were derived and verified. Hardware standards for 1.5-inch circular beam pipe were made and tested. Standards for elliptical beam pipe and other pipe radii for the Advanced Photon Source (APS) storage ring components are being designed. The measured impedances indicate that the ceramic pipe is purely capacitive.

I. Introduction

The wire method has been widely used for beam coupling impedance measurements of various beam pipe components. When the wire diameter is much smaller than the dimension of the beam pipe cross section and the operating frequency is below cutoff, the results obtained by the wire method are similar to the real beam impedance when excited by a particle bunch. Figure 1 shows the experimental system setup for wire measurements. Once the S-parameters of the device under test (DUT) and reference chamber (REF) are obtained, the longitudinal impedance $Z(\omega)$ is given by [1]

$$Z(\omega) = 2Z_0 \left(\frac{S_{21}(REF)}{S_{21}(DUT)} - 1 \right) \tag{1}$$

where Z_0 is the characteristic impedance of the reference chamber.

As depicted in Fig. 1, the transitions T_1 and T_2 are necessary for adapting the wire/chamber structure to the regular coaxial cable connected to the network analyzer. These transitions are not part of the device under test and their influences have to be removed from the measured S-parameters. Previously, the calibration was made up to A and B planes where the coaxial cables end, using the conventional Short-Open-Load calibration method with HP calibration kits. The influence of the transition cannot be truely removed or de-embedded from the response. Making a custom set of Short-Open-Load calibration standards for a general beam pipe structure would be a very difficult task. TSD/TRL/LRL calibration techniques provides a way to calibrate the system up to the A' and B' planes using simple and easy-to-make standards.

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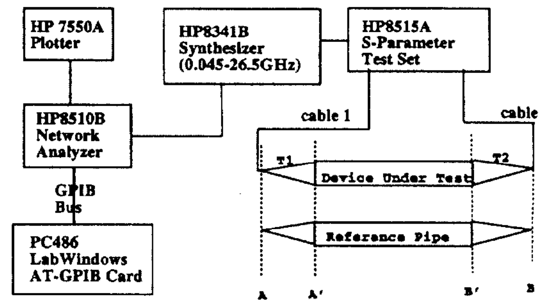

Figure 1
Experimental system setup for beam coupling impedance measurements using the wire method

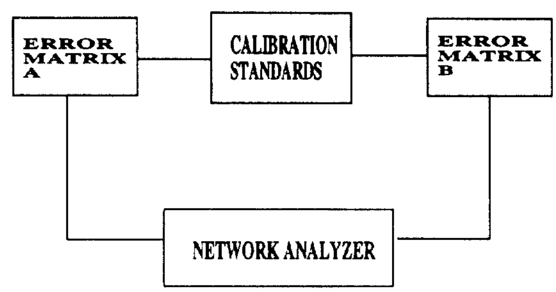

Figure 2
A general error model for network analyzer calibration

II. Description of Algorithms

Derivations of the TSD/TRL/LRL procedure can be found in [2],[3] and [4]. A brief overview of the algorithms are given below to show their differences and advantages.

The error model for the calibration is shown in Fig. 2. Error matrices A and B are determined by inserting different sets of calibration standards between them. For TSD/TRL/LRL calibration, each uses the three standards Thru(T), Short(S)/Reflect(R) and Line(L)/Delay(D).

Thru is a zero length transmission line with S and T parameters given by

$$S_T = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad T_T = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}. \tag{2}$$

Line or Delay is a matched transmission line with length ℓ. Its S-parameters are given by

$$S_L = \begin{pmatrix} 0 & e^{-\gamma\ell} \\ e^{-\gamma\ell} & 0 \end{pmatrix}. \tag{3}$$

Short has a reflection coefficient of $\Gamma_S = -1$. Reflect has an unknown reflection coefficient Γ_R, but the sign of its real part, $Re(\Gamma)$, has to be known.

Starting from the measured uncalibrated S or T parameters of Thru, Line/Delay and Reflect/Short, the following T-parameters can be derived [2],

$$\frac{t_{A11}}{t_{A21}}, \frac{t_{A12}}{t_{A22}}, \frac{t_{A11}}{t_{A22}}, \frac{t_{B21}}{t_{B22}}, \frac{t_{B12}}{t_{B11}}, \frac{t_{B11}}{t_{B22}}, \Gamma_R, e^{2\gamma l} \quad (4)$$

where A and B represent the error matrices A and B. From these intermediate results, the following S-parameters are obtained,

$$S_{A11}, S_{A22}, S_{A12}S_{A21}, S_{B11}, S_{B22}, S_{B12}S_{B21} \quad (5)$$

and

$$S_{A12}S_{B12}, S_{B21}S_{A21}. \quad (6)$$

The reflection parameters are obtained explicitly, but the transmission parameters are all in the form of products.

The first three quantities in Eq. (4) are obtained after taking some square roots. It is a problem of choosing the appropriate sign of the square roots. For the first two quantities $\frac{t_{A11}}{t_{A21}}$ and $\frac{t_{A12}}{t_{A22}}$, the correct choice of the sign would give

$$\left|\frac{t_{A11}}{t_{A21}}\right| > \left|\frac{t_{A12}}{t_{A22}}\right|. \quad (7)$$

The third quantity in Eq. (4) $\frac{t_{A11}}{t_{A22}}$ is related to the reflection coefficient of the reflect standard Γ_R by the following equation

$$\Gamma_R = \frac{S_{R11} - \frac{t_{A12}}{t_{A22}}}{\left(\frac{t_{A11}}{t_{A22}}\right)\left(1 - \frac{S_{R11}t_{A21}}{t_{A11}}\right)}. \quad (8)$$

Thus the correct choice of $\frac{t_{A11}}{t_{A22}}$ would give the correct sign of $Re(\Gamma_R)$.

Summarizing the three calibration techniques, TSD calibration requires a thru, which may have a finite length ℓ_1, a short standard with $\Gamma_S = -1$, and a delay line of unknown length ℓ_2. It is required that $\ell_2 - \ell_1 < \lambda_{max}/2$, where λ_{max} is the wavelength of the maximum frequency of the span.

TRL calibration requires a zero length thru, a reflection standard with unknown reflection coefficient Γ_R, and a delay line of unknown length ℓ. The sign of the real part of the reflection coefficient $Re(\Gamma_R)$ has to be known. It is also required that $\ell < \lambda_{max}/2$.

LRL calibration requires a thru of known length $\ell_1 > 0$, a delay line of known length $\ell_2 > \ell_1$, and a reflection standard of unknown Γ_R with known sign of $Re(\Gamma_R)$. Lengths ℓ_1 and ℓ_2 should satisfy $\ell_2 - \ell_1 < \lambda_{max}/2$.

III. Measurement Results

TSD/TRL/LRL calibrations have been implemented on a 486PC running LabWindows 2.2.1 for DOS. A GPIB interface connects the PC and an HP8510 network analyzer. The program has a graphical user interface for operation and data presentation.

A set of hardware was made for measuring a bellows and a ceramic pipe. The circular beam pipe has an inner diameter of 1.36 inch. The calibration standards as well as the device under test were placed between two tapers to adapt to a 3.5mm coaxial cable. The center wires are also tapered with a maximum diameter of 0.25 inch. The characteristic impedance of the structure is 102Ω. The cutoff frequency of the first higher mode is 10.13 GHz.

The LRL calibration was performed with a thru of $\ell_1 = 0.5$ inch and a delay of $\ell_2 = 1.5$ inch. The valid frequency range for these two standards is given by $\ell_2 - \ell_1 < \lambda_{max}/2$ or $f_{max} = 6GHz$. The operating frequency of the measurement is chosen to be 1-3 GHz, which is well below the cutoff frequency of the pipe. The corrected S-parameters of the device under test were ported to a Sun SparcStation, and their impedances calculated using Eq. (1).

The S-parameters of the reference chamber are calculated from Eq. (3), where ℓ is chosen to be the same as the length of the device under test. The ceramic beam pipe is braced on two stainless steel flanges and the total length of the component is 7cm. The length of the bellows is 9.35cm. The propagation constant γ is given by $\gamma = j\frac{\omega}{c}$, where c is the speed of light. This is true when there is only TEM mode in the pipe.

Figure 3 through 6 give the measured longitudinal beam coupling impedances of a bellows and a ceramic pipe. The real parts of the impedances are positive, representing resistive losses. The imaginary part of the ceramic pipe impedance is purely capacitive.

IV. Conclusion

TSD/TRL/LRL calibrations are implemented for wire method impedance measurements. The reference planes of the measurement are close to the device under test and the influences of the transitions are calibrated into the system error matrices. This capability is achieved with simple and easy-to-make calibration standards. The criterion for choosing the appropriate sign of the square root has been worked out. Impedance measurements can be performed with accuracy even without a reference chamber. Longitudinal impedances of a bellows and a ceramic beam pipe are measured.

V. Acknowledgement

Special thanks must be given to D. Freeman for his contribution to the coding of the calibration procedure in the C language and his design of the graphic user interface in LabWindows.

VI. References

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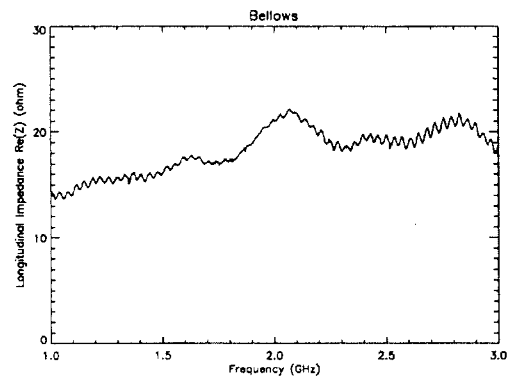

Figure 3
Longitudinal beam coupling impedance of a bellows, real part Re(Z)

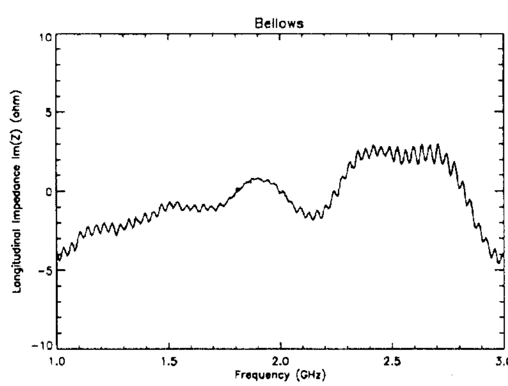

Figure 4
Longitudinal beam coupling impedance of a bellows, imaginary part Im(Z)

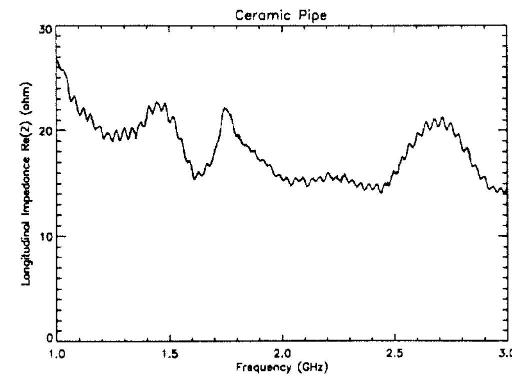

Figure 5
Longitudinal beam coupling impedance of a ceramic pipe, real part Re(Z)

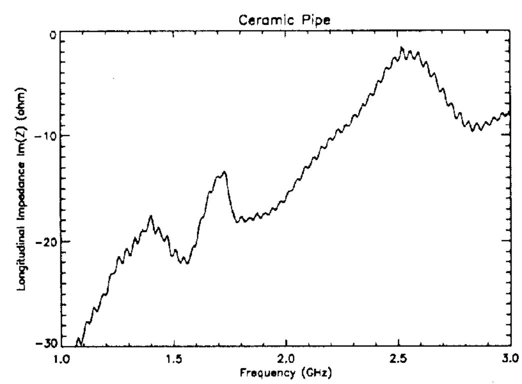

Figure 6
Longitudinal beam coupling impedance of a ceramic pipe, imaginary part Im(Z)