A Critical Survey of Stretched-Wire Impedance Measurements at Fermilab

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Abstract

Bench measurements of the impedance of various beam line components, as well as several test structures have been carried out using cavity perturbation and stretched wire methods. Several pitfalls of the wire measurement technique have been uncovered and improvements were developed to resolve ambiguities and improve overall accuracy. In this paper, we summarize the results of our findings concerning measurement techniques, accuracy limitations, and the comparison with numerical simulation of model test structures.

I. INTRODUCTION

A concerted effort is being made at Fermilab to understand and control the contributions of various beamline components to the overall impedance seen by the beam, in order to prevent the onset of various instabilities under normal operating conditions, and at the increased intensity levels expected in the near future. Several methods have been used to determine the effective impedance of a given structure, including (a) cavity perturbation techniques using small, suspended beads [1], (b) beam measurements using a coasting beam in situ [2] and (c) bench measurements employing a thin, coaxial wire stretched along the beam path. [3] Of these methods, the stretched wire techniques are most commonly used because of the ease with which the measurements may be carried out. However, a number of measurement difficulties arise in the use of stretched wires, owing to the fact that reflections may readily occur on a coaxial wire, but not on a high energy beam.

II. STRETCHED WIRE METHODS

The measurement of impedance is divided into two subareas: (a) longitudinal impedance, which can produce a beam energy loss, and (b) transverse impedance, which is responsible for a transverse deflection of the beam. In its most general form, an object in the beam line can be considered to be a 2-port network, involving both shunt and series currents, as shown in Fig. 1, (a) and (b). The two models are equivalent, but energy loss associated with longitudinal fields, i. e. longitudinal impedance, is best determined from the normalized Pi-network, as

$$Z_{||} = \frac{Z_o}{Y_{12}} \tag{1}$$

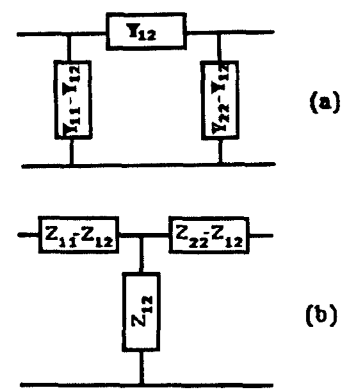

Fig. 1 (a) Pi network model and (b) T network model

while an equivalent shunt impedance is found from the normalized T-network to be

$$Z_S = Z_0 Z_{12} \tag{2}$$

We note the distinction between this perpendicular impedance and the transverse impedance described previously. The above perpendicular impedance is not necessarily associated with a net transverse force on the beam. Using the familiar S-parameters, which are the quantities usually determined from the modern network analyzer, the above impedances are expressed as

$$\frac{1}{Y_{12}} = \frac{1 + S_{11} + S_{22} + \Delta_s}{2\,S_{21}}$$

$$Z_{12} = \frac{2S_{21}}{1 - S_{11} - S_{22} + \Delta_s} \tag{3}$$

$$\Delta_s = S_{11}S_{22} - S_{21}^2$$

We note that in the limit of negligible shunt losses,

$$Z_{12} \to \infty\,,\quad S_{11} = S_{22} = 1 - S_{21} \quad \text{and} \tag{4}$$

$$Z_{||} \to 2\,Z_0\left(\tfrac{1}{S_{21}} - 1\right)$$

which is the usual result quoted in the literature. [4] However, this condition does not hold in general, and it can be expected that the application of this expression to cases where the shunt

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impedance is non-negligible will be in error. In the case of a high energy beam, no TEM reflected waves can exist, implying $S_{11} = 0$, which is a major distinction from the case of a stretched wire.

As such, the effects of reflections on the stretched wire need to be carefully eliminated from the measured data, which requires a knowledge of the full 2-port scattering matrix for the unknown device. This requirement leads to the necessity of developing an accurate model for the test fixture used to carry out the measurements, which must include any transformers used to make a transition from the 50Ω line to the (typically a few hundred ohm) stretched-wire. Generally, one of two methods for effecting a wideband transformation is used: (a) cone transformers which vary the characteristic impedance gradually along their length and (b) resistive matching networks. The practical length limitation of cone transformers limits their frequency range to above a few hundred MHz, while parasitic reactances of resistive matching networks restrict their usage to below about 1 GHz. The effect of these transformers can be represented in general by linear 2-port networks cascaded with the test device, as shown in Fig. 2.

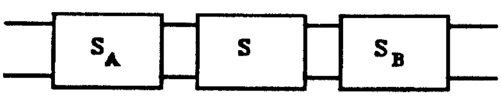

Fig. 2 Cascaded measurement network. S represents the S-parameters of the unknown impedance.

The measurement problem becomes one of de-imbedding the unknown S-parameters from the external measurements of the system.

We have used two techniques to carry out the de-imbedding process. First, the full 2-port S-parameters of the test fixture alone are measured with standard (open-short-load) calibrations to remove the cable contributions. Using a least-squares circuit optimizer [5] with the model circuit shown in Fig. 3,

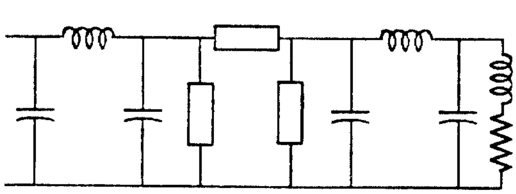

Fig. 3 Lumped element model of the measurement fixture. The unknown forms a 2-port network in the center.

the impedance is deconvolved from the data using standard circuit analysis. Resistor matches have been used at the fixture ends to reduce reflections and facilitate deconvolution. We note that shunt terms have been ignored here. This approach yields satisfactory results over about a 2-octave bandwidth, until the lumped element end models break down. The second process does not depend on termination standards, but uses two lengths of line of characteristic impedance Z_0, differing by about 1/4 wavelength, as well as two shorts placed at the reference plane. This Through-Short-Delay (TSD) procedure [6] affords the advantage of removing the effects of nonideal transformers and cables in one operation. It also permits a high degree of spatial resolution in the impedance measurement. The effective bandwidth of the method is not limited, but several delay lengths may be required to cover the desired band.

De-imbedding has been carried out using the above procedure for a simple test cavity, as shown in Fig. 4. The

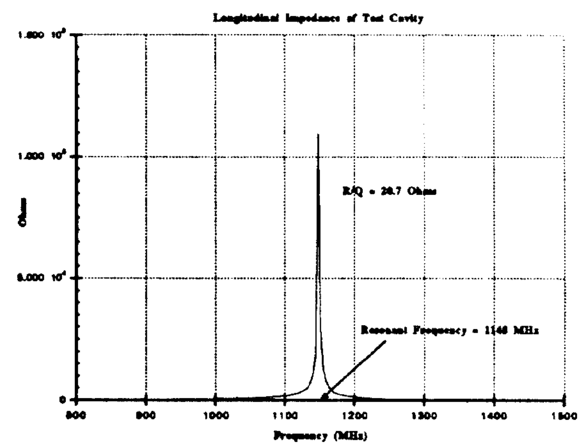

Fig. 4 Real part of $Z_{||}$ for a test cavity, derived from measurements by de-imbedding.

relatively low impedance of the stretched-wire (326 Ω) lowers the Q of the cavity substantially. However, since the R/Q value is preserved, the actual Q can be recovered. The actual Q values compare favorably with weakly coupled probe measurements.

Another problem occurring with wire measurements occurs when more than one source of impedance exists in a given device, such as the dual gap booster cavity of Ref. [7]. Since cavity gap impedances are typically large, significantly large standing waves can occur on the wire between the gaps, introducing spurious resonances into the system. There is no simple means of determining both gap impedances from a single, external S-parameter measurement. One solution of this problem is to only measure one gap at a time, i.e. via S_{11} measurements, using a termination at the unexcited end of the wire. This approach was used effectively in producing the booster data above. An alternative approach consists of inserting a miniature laser/light pipe system into the beam pipe, as shown in Fig. 5. The light pipe does not couple the gaps together, while permitting an intrinsically more accurate S_{21} measurement of the gap impedance. An equivalent, but less perturbing method involves the use of probes instead of a stretched-wire. The probes form a capacitive divider whose shunt loading impedance on the test device can be made exceedingly high, subject to the dynamic range of the system. With the addition of in-situ, low-noise amplification, we have extended the dynamic range of our measurement to 180 dB, facilitating highly non-perturbing measurements.

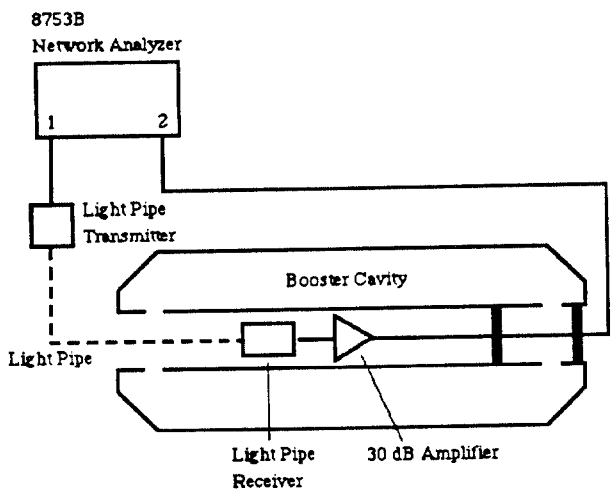

Fig. 5 Single gap S_{21} measurement using a light pipe to avoid inter-gap coupling.

We have compared the results of experimental measurements of the longitudinal impedance with theory for a simple pillbox cavity, where analytic solutions are known. Moreover, the cavity was of a sufficiently small size to force the resonant frequencies to be in a range where careful determination of the transformer impedance was required. We compare the results of the wire method with a lumped circuit model with the theoretical values in Table 1. It is observed that the resonant

Table 1

	Theory	Measurement
f_0 (GHz)	1.134	1.147
	2.621	2.670
R/Q	27	20.7
	21	15.0

frequencies are somewhat shifted and Q values of the unloaded cavity considerably exceed the wire-loaded values, but the R/Q values are in reasonably good agreement with the theory.

III. DISCUSSION AND SUMMARY

We have developed stretched-wire impedance models that include both longitudinal and shunt components, and have studied the effects of non-negligible reflections on measurement interpretation and accuracy. Using the TSD calibration method, we have devised an accurate measurement technique for determining the local impedance of a given structure, and have used transmission probes to greatly reduce the loading of high-Q devices.

Several problem areas remain, however, which require further study. There is presently no stretched-wire method of determining the individual contribution of physically separated objects to the overall impedance of a distributed structure, owing to the possibility of reflected waves along the wire. A recently proposed approach involving time-resolved wave packets may of use in this case, though the maximum measureable Q must be traded off against spatial resolution. At Fermilab, there is no general approach to impedance measurements above the beam pipe cutoff frequency, where higher modes are observed to occur due to discontinuities in the system. There is a need to develop single-mode wave launchers and receivers to facilitate measurements in this domain. Finally, it is desireable to apply similar methods to the measurement the transverse impedance directly.

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