THE STRETCHED WIRE METHOD: A COMPARATIVE ANALYSIS PERFORMED BY MEANS OF THE MODE MATCHING TECHNIQUE

M. R. Masullo, V.G..Vaccaro#, INFN-Napoli and Federico II University, Napoli, Italy
M.Panniello, Federico II University, Napoli, Italy

Abstract

The Wire Method (WM) for Coupling Impedance (CI) evaluations is quite appealing for the possibility to make bench measurements on the Device Under Test (DUT). However, it is not entirely reliable because the stretched wire perturbs the boundary conditions, introducing a TEM wave with a zero cut-off frequency. We expect that, for frequencies smaller than the hollow pipe cut-off, this behaviour produces an additional power loss which drastically lowers the high Q resonances of the DUT. Above cut-off frequency, the impact of the wire is not as dramatic as below cut-off. The Mode Matching (MM) Technique will be used to simulate the WM measurement. In this way, one may get a result which is not affected by the intrinsic errors of experimental measurements. The same method will be used to get, according to its standard definition, the CI of the real structure. The two results will be compared in order to define the frequency ranges in which they agree or disagree. As expected, large discrepancies appear below cut-off frequency while above cut-off, for certain ranges of parameters, an acceptable agreement is found.

INTRODUCTION

In particle accelerators, the interaction between beam particles and their surroundings have attracted the attention of physicists and engineers since the beginning of the systematic study of coherent instabilities. One may affirm that they were born together because of their complementarities. The strength of the interaction is characterized by the CI and Wake field of accelerator components. For each new particle accelerator design, careful establishment of an impedance budget is a prerequisite for reaching desired performances. Therefore, theoretical analyses, computer simulations, and experimental measurements of CI of accelerator components are critical tasks in accelerator research, design, and development.

The ideal experimental measurements should be done by using the beam itself. However, in most cases this solution is not viable and one must resort to bench measurement techniques. For CI evaluations, the WM is a common and appreciated choice. Its basic idea consists in replacing the current pulse produced by a beam with a current pulse having the same temporal behaviour, flowing through a wire stretched along the beam axis. This technique was first proposed in the first half of ’70, based on consideration of intuitive type. By means of WM, Faltens et al. [1] measured the wall contributions to the CI. M.Sands e J.Rees (1974) [2] measured the power loss by an electron bunch traversing a resonant cavity. At BNL and at CERN, the method was employed to measure the Longitudinal and Transverse CI [3,4] of a kicker in the frequency domain. We intend to perform a numerical comparison between the bench measurement using the WM and the real model, by means of the well known MM Technique.

#vaccaro@na.infn.it

The MM Technique consists into splitting the system in subsets (cavities and waveguides) characterized by homogeneous boundary conditions, and then into expanding the field as a superposition of the relevant eigenmodes. The MM technique has been already used for computing interactions between moving charges and surrounding equipment. Gluckstern [5] gave general formulas for tanks connected to pipes of arbitrary shapes in the high frequency limit; Henke [6] studied the response of an array of pill-box cavities; Kheifets [7] concentrated his attention to the CI of a pill-box cavity above the pipe cut-off frequency. Up to now no one took into account finite conductivity in a non-perturbative way. It has been proven [8] that the MM technique gives quite reliable results in simulating the measurements made with the WM. This result gives us a reasonable assurance about using the MM technique for comparative experiments on WM.

THE REAL MODEL AND THE NUMERICAL EXPERIMENT

The MM Technique has been applied to the study of a lossy pill-box cavity in two different configurations: fed by a modulated charged particle beam current and by a coaxial wire. For the first configuration, the main feature of this approach is to give accurate numerical results for the longitudinal CI of a real pillbox in a wide range of frequencies. Scattering matrix for the second configuration is also produced, determining the Longitudinal CI by means of a post processing formula. Both results are obtained with a light computation apparatus.

The Real Model

The object of this section is to determine the response of a pill-box cavity fed by a charged particle beam moving with arbitrary velocity along the symmetry axis ($v = \beta c$, even if we use a relativistic beam when compare the real model with the WM results). The behaviour of any passive device inserted in a cylindrical vacuum chamber dramatically changes passing from below to above the cut-off of the vacuum chamber. It is worth of note that this frequency is connected only to the dimensions of the vacuum chamber cross section and that below this frequency no wave is allowed to propagate.

Below cut-off, since no energy is allowed to freely flow inside the pipes, we expect that at some frequencies (related to the device resonances) high Quality factor (Q) CI's will appear strongly dependent on wall conductivity. Remark: in case of perfectly conducting cavity, the real part of the CI must be strictly zero up to the cut-off frequency.

Above cut-off, the real part of the CI may be different from zero: a certain amount of the energy, released by the beam into the room delimited by the discontinuity of the device, is allowed to flow into the vacuum chamber. Since the phase velocity of its EM field is larger than the particle velocity, the mean power exchange between the beam and the field is zero: in sum, this energy is irreversibly lost by the beam and as a consequence, a non-zero real part appears in the CI. The finite conductivity of the walls introduces additional losses that are always rather small and sometimes negligible in respect to the above mentioned radiative losses, so the C.I. will be almost insensitive to the pipe/cavity conductivity.

The Numerical Experiment

One can see that the electric charge associated to a particle beam crossing through a generic vacuum chamber produces an electromagnetic field inside of it, which generates a charge distribution and induces currents on the device walls. Stretching a metallic wire along the cavity axis, and neglecting the coupling effect with the inside radial line, it makes the cavity similar to a coaxial transmission line. It is worth of note that the introduced perturbation totally modifies the boundary conditions of the system. In fact, the section of the fundamental structure obtained will have not the simply connection property. As known, this has as a consequence the possibility to have TEM modes and all frequencies propagating modes as a solution of the Maxwell equations. Nevertheless, carrying a current pulse having the same temporal behaviour of the one related to the beam on the conductor, it has been shown that the TEM field produced by this pulse exactly reproduces the field generated by the beam, if the initial energy equals the bunch one, unless in the immediate proximity of the wire. The intuition suggests that, independently by the wire presence, the field generated initially by the current pulse is the same of the one produced by the beam, provided that the wire dimensions do not perturb the electromagnetic field existing without the wire. After this, the first charges and current induced on structure walls can be held equal in the two cases. This means that in a very first moment the cavity doesn't recognize the boundary condition variation. All affirmed till now, based exclusively on intuitive considerations, lead to believe that if the bunch duration results to be small in comparison to the time of relaxation of the cavity with the wire, then the energy loss by the impulse that circulates on the conductor, and lost as electromagnetic energy, will be close to the energy lost by the particles beam emulated. However, we may state since now that this method intrinsically will give inaccurate results below cut-off. The presence of the wire and then the TEM wave, which intrinsically has a zero cut-off frequency, has as a consequence the depleting of resonant frequencies because of power drained in the pipes by the TEM mode. On the other hand we expect that, somewhere above cut-off frequency, where the TEM wave effect should be less strong, this method might give fairly good results. The experiment is done on the same structure as the previous section, where a wire substitutes the beam.

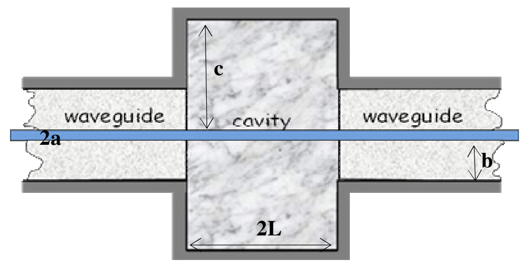

Figure 1: Scheme of the experimental setup.

It is worth of note that, since the coaxial configuration has a multiple connection of first order, it can support at least one TEM mode: it is quite natural to take this mode as the forcing source. In this case, we will find the scattering parameters first, and then we will use them to determine the CI. In addition, one has to remember that the presence of the wire changes the DUT characteristics. Inserting the wire, the waveguides behave like coaxial cables and the cavity is treated as a coaxial cavity. Therefore, the cavity modes and the waveguide waves are different from the previous case.

Furthermore, in the case of the WM it is not necessary to introduce losses due to finite conductivity of the walls; indeed, below cut-off the power lost because of the TEM wave is so larger than the one dissipated in the cavity that the Q is dominated by the former ones. Above cut-off frequency, the above mentioned statement is a fortiori valid.

RESULT COMPARISON

In a previous work [9], it is shown an improved WM to determine the DUT CI by means of scattering parameter measurement:

$$Z_{\parallel} = Z_0 \ln\left(\frac{S_{21}^R}{S_{21}^D}\right)\left(1 + \frac{\ln S_{21}^D}{\ln S_{21}^R}\right)$$

We intend to resort to the MM technique in order to obtain the needed scattering parameter S_{21} to be introduced in the above formula, and to compare the result with those obtained applying the MM Technique to a real model.

In Figure 2 is reported, for a copper Pillbox, the comparison between WM numerical experiment and the real model up to a frequency of 32 GHz, well above the cut-off frequency (7.3GHz). The adopted x-axis is the wave number normalized to the pipe radius. This choice allows the cut-off frequency to lie on the value 2.4, regardless of the parameter width. In Figure 3 another example (whose cut-off frequency is 28 GHz) is reported evaluated until 0.12THz.

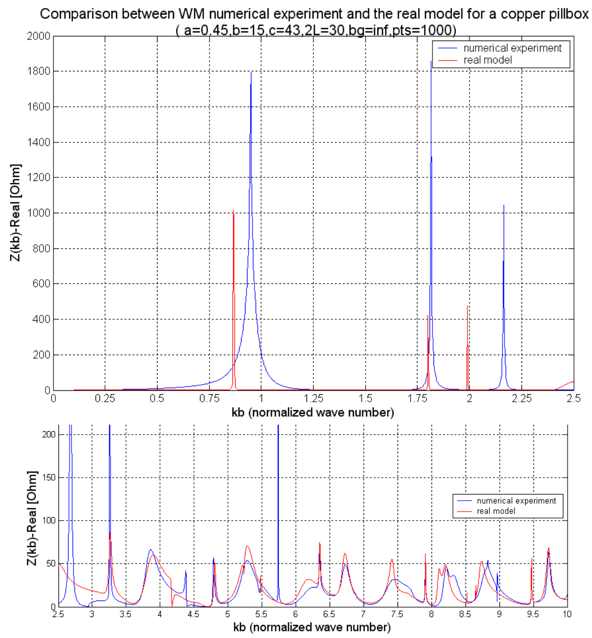

Figure 2: Copper pillbox (a=0.45mm; b=15 mm; c=43 mm; 2L=30 mm; βγ>1000).

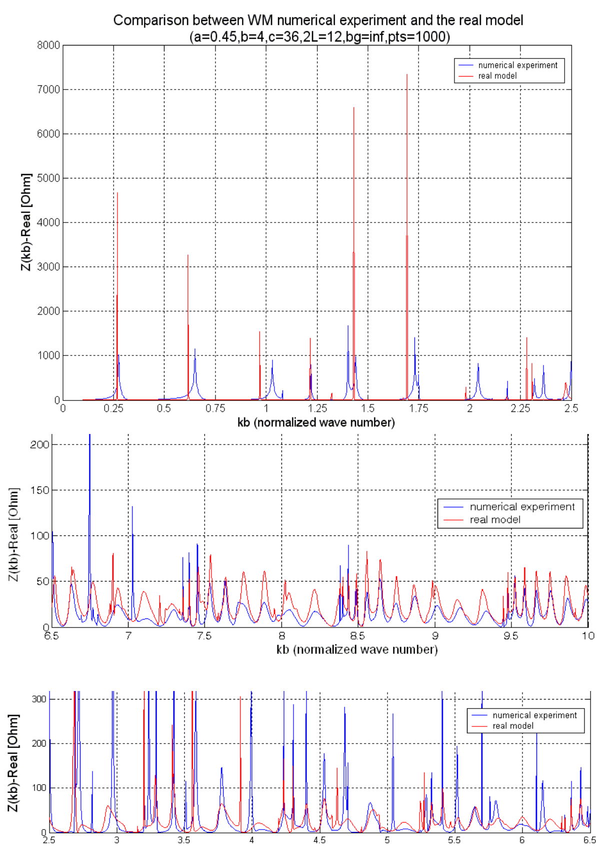

Figure 3: Copper pillbox (a=0.45mm; b=4 mm; c=36mm; 2L=12 mm; βγ>1000).

According to fundamental arguments on physical behaviour we expect some discrepancies between the two results. It is clear that, below the cut-off frequency, the WM disagrees with the real model.

As already said in previous sections, this phenomenon is to be ascribed to the presence of the wire which perturbs the measurement making uncertain some results. The presence of the wire, indeed, shifts the cut-off frequency to zero by introducing a TEM mode that is allowed to propagate because coaxial cables support it. This implies an additional loss of energy from the resonant cavity and a consequent depletion of the quality factor: broadband impedance behaviour appears in the forbidden region. In the range of frequencies 30% larger than the cut-off it is quite striking the agreement between the behaviour of the wire measurement and the real model. Negligible perturbations appear in this range.

CONCLUSIONS

We reached the important accomplishment to understand the limitations of bench measurements done by means of the stretched wire method. It has been proven that this method intrinsically will give inaccurate results below cut-off. As already mentioned, this behaviour is due to the presence of the wire that introduces a TEM wave, which intrinsically has a zero cut-off frequency. All the resonant frequencies are depleted because of power drained in the pipes by the TEM mode. Above frequency 30% larger than the cut-off, there are indications that this method may give fairly good results.

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