COAXIAL WIRE METHOD ADAPTED TO WEAKLY COUPLED RESONATOR MODE FOR LHC RF FINGERS EVALUATION

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Abstract

In high intensity particle accelerators, RF contact fingers are commonly used to carry the image current induced by the beam. In addition, they provide an impedance reduction by shielding the outer bellows that are required to compensate mechanical displacements between different components. In order to assess the resulting beam impedance from a specific bellows/RF finger configuration, RF measurements are routinely carried out by means of a coaxial wire method. During these measurements, it was observed that cavity modes in the volume between the fingers and the bellows undulation arise. These resonances occur at significantly higher frequencies than the expected frequency range of interest for such a device. Due to their broadband nature, the tails of the imaginary part of these resonances reach into the lower frequency range of interest where they contribute to the beam coupling impedance of the device. For proper evaluation of this contribution, a time domain delay technique in TDT (time domain transmissiometry) was used in order to overcome shortcomings that arise if the classical coaxial wire method is applied to these structures. We present the theory of our method and discuss it in view of the data obtained on deformable fingers that were studied for the LHC.

INTRODUCTION

RF contact fingers are used to carry the beam image current in locations where bellows are required to absorb primarily longitudinal movements of the adjacent vacuum chambers caused by thermal expansion. This way, RF contact fingers reduce beam coupling impedances that arise from accelerator equipment in the case that the equipment is structurally deviating from the ideal uniform beam pipe shape. Therefore, wire or probe measurements are routinely carried out on new or modified accelerator equipment of the different machines. A new RF-finger design was suggested recently [1], after some problems could be observed with existing RF-fingers in the Large Hadron Collider (LHC) [2]. The main improvement of these fingers is that they are no longer sliding in the case of longitudinal movements of the vacuum chamber, instead the fingers are deformable and allow a continuous connection between adjacent vacuum chambers by stretching their convolutions. However, during the measurement of these RF-fingers, it was observed that cavity modes in the volume between the fingers and the bellows undulation become noticable. For proper evaluation of this effect, a time domain technique can be used that allows to overcome shortcomings that arise when the coaxial wire method is applied in the classical way.

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MEASUREMENT AND DUT

The device under test (DUT) consists of outer bellows around the beam pipe which carries the slotted RF-fingers with 2 or 3-convolutions (see Fig. 1). This results in a coaxial-like structure that electromagnetically shapes two-coupled resonators and thus supports multiple modes. In addition, the insertion of the measurement wire produces a "nested" coaxial structure with an inner and an outer volume (as is indicated in Fig. 1).

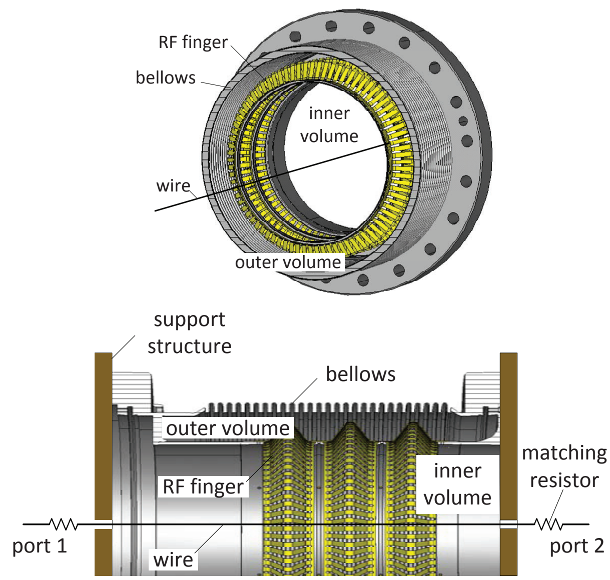

Figure 1: Top: transverse cross-section, and bottom: longitudinal cross-section of nested coaxial structure consisting of outer (stainless steel) bellows and (copper-beryllium) 3-convolution RF-fingers with centered measurement wire.

While the standard wire measurement method is a well-known technique, and its different variants are described in many textbooks, e.g. [3], it is equally well known that the wire method is unsuited for the measurement of cavities due to the unavoidable strong coupling on high-Q resonant modes. For cavities, measurements with EM-probes should be carried out instead. Surprisingly, on the set-up with the RF-fingers, *cavity modes* could be observed even while measuring with the wire method. These cavity modes were manifesting themselves as negative peaks in the transmission signal (see Fig. 2). We thus carried out transmission measurements with probes placed on axis in the inner volume. With these probes, however, we could determine only resonances from the inner structure which could be easily proved by variation of the coupling between the inner and the outer volume. For example, stretching the structure so that the gaps between the fingers reduces did not change the coupling. Consequently, the resonances seen *with the wire*

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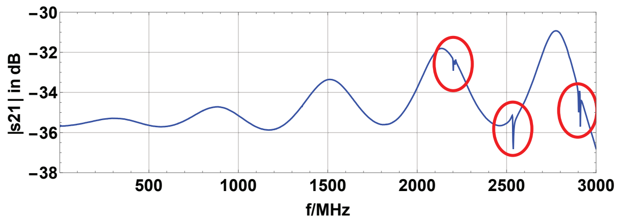

Figure 2: Magnitude of transmisstion S-parameter signal S_{21} of cavity modes observed with the wire method in frequency domain. Data from 2-convolution RF-fingers.

develop in the volume between the outer bellows and the RF-fingers, and are a result from the two-coupled resonator structure of this geometry. Further, they occur at frequencies significantly above 1 GHz, but tails of their imaginary part of the resulting beam coupling impedance reach into the lower frequency range of interest. This way, they add to the overall impedance of the object. Unfortunately, from the wire measurement in frequency domain, these resonances cannot be evaluated and EM-simulations are difficult due to the filigrane shape of the RF-fingers. Fig. 3 shows the 2-convolution RF-fingers on the measurement bench without the outer bellows mounted (top) and with the outer bellows in place (bottom).

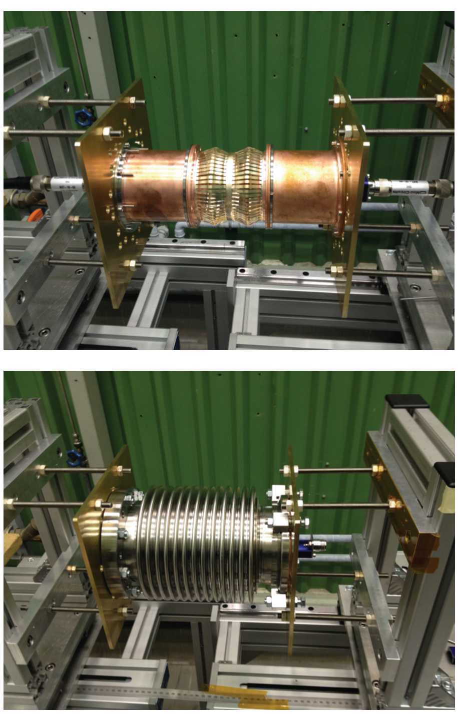

Figure 3: Top: Picture of the RF-fingers with 2-convolutions, bottom: RF-fingers in outer bellows on measurement bench.

Measurement Principle in TDT

For a proper evaluation of the observed resonances above 2 GHz, we used a time domain transmissiometry (TDT) technique combined with the coaxial wire method. It should be noted that while time domain reflectometry (TDR) is a commonly used method for RF-measurements, however, it is unsuited here due to the large number of multiple reflections within the structure. Though TDT is based on the same algorithms, it is much less popular nowadays and mainly used in geology, e.g. for soil evaluations [4, 5]. We use the TDT to determine changing electrical lengths of the set-up from which the imaginary parts of the resonances can be estimated. The wire measurement is carried out in a standard set-up with a copper wire of 0.5 mm diameter connected to matching resistors [3] making use of the fact that line impedance of a circular coaxial line with outer diameter D and inner diameter d (i.e., the wire diameter) calculates to $Z_L = 60\Omega \ln(D/d)$. From the large frequency range (1 MHz - 3 GHz), a wide band matching is desired, hence lumped element resistors were soldered in series to the wire to obtain a reasonable match with the 50 Ω of the vector network analyser (VNA) port. The pulsed signals in time domain allow the determination of electrical lengths which change when the bellows and the RF-fingers are stretched or compressed. Fig. 4 shows the measurements taken on the 2-convolution RF-fingers with bellows in TDT and the corresponding electrical length prolongations. Two 10dB-attenuators were added on both sides of the structure to reduce the effect of multiple reflections due to the non-ideal matching of the lumped resistors over the entire frequency range. As can be seen in the plot, some reflections are still visible in time domain, these are considered to be insignificant. It should be noted that to obtain a proper signal in time domain, theoretically gating would be possible. In our case, however, due to the rather short length of the DUT, pulses with overlapping tales are showing up which make the signal evaluation in frequency domain ambiguous, if gating is used.

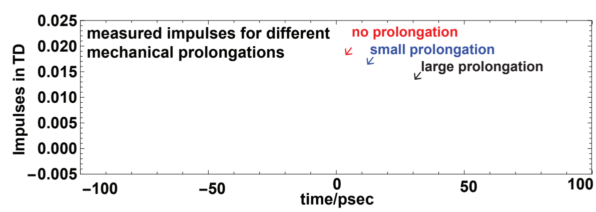

Figure 4: Illustration impulse signals taken with the wire method in TDT measurement principle for different mechanical prolongations of the RF-fingers

Measurement Results

The difficulty now is, that with the extension of the RF-fingers, not only the mechanical length changes, but due to the closing of the RF-fingers with extension, the set-up *geometry* modifies as well. It is therefore crucial to disentangle the mechanical and electrical length changes. Table 1 shows the deviations of the mechanical and electrical length changes measured in TDT (i.e. relative values in mm) on the 2-convolution RF-fingers. Similar results were observed from the measurements of the 3-convolution RF-fingers. It can be seen from the table that the set-up consistently measures electrically *shorter* lengths than what is expected as a mechanical length from the prolongation, i.e. the mechan-

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ical length prolongation is only partially transmitted into an electrical length prolongation. This can be explained by the fact that a prolongation of the set-up results in a reduction of the coupling from the beam-simulating wire towards the outer volume, since the fingers close when the structure prolongs. Consequently, a prolongation of the structure yields a reduction of the loss mechanism that takes place when the measurement signal excites modes in the outer volume, similarly to a damping effect that can be described with an electrical phase delay. It can equally be observed that the first step of mechanical prolongation of 10 mm caused an increase of electrical length of only about half, i.e. 5 mm, whereas further mechanical prolongations of additional 5 mm (i.e. from 10 mm to 15 mm mechanical prologonation, and from 15 mm to 20 mm mechanical prolongation, see table 1) are reproduced in electrical prolongations of almost equal lengths (i.e. 4 mm each). This is an indicator that the RF-fingers close well, thus reduce the coupling. Consequently, in the state of un-stretched RF-fingers, the opening between individual fingers is largest, therefore for the first step of mechanical prolongation, the detected difference between mechanical and electrical prolongations has to be biggest.

Table 1: Comparison of measured mechanical and electrical lengths by means of TDT (relative values in mm). Data from 2-convolution RF-fingers with bellows mounted.

Mechanical prolongation [mm]	0	10	15	20	24
Total additional electrical length [mm]		5	9	13	16
Difference [mm]		5	6	7	8

Such a direct measurement of a phase change *in frequency range* is difficult if not impossible to evaluate in a precise manner, whereas in TDT, we can assume a length difference to be linear in a first approximation. Thus, the length difference in TDT can be directly resolved and expressed as a change in the signal's phase.

As a cross-check of the method, it was tested that for an extension of the geometry of the RF-fingers without the outer bellows mounted, the prolongation of the electrical and the mechanical lengths reproduce as electrical delays within the precision of the measurement. It should be mentioned that the use of electromagnetic probes, usually the standard method to determine high-Q resonances would have required to drill a hole in the bellows in order to allow probe access. This would have made our measurements destructive on the DUT and hence were not considered.

Comparison of RF-Fngers with/without Bellows

The comparison of the measurements of the RF-fingers with and without the outer bellows mounted allows to rule out the influence of the RF-fingers structure itself, i.e. as was explained above, we only evaluate phase changes due to electrical delays that can be attributed to the imaginary part of impedances from resonances located at higher frequencies. This is valid as long as we stay in the linear regime of the phase response. In this case, the electrical delay T_{del} can be determined from:

$$t_{\mathrm{del}}/\mathrm{s} = \frac{\Delta\varphi/\mathrm{rad}}{\Delta\omega\ \mathrm{s/rad}}$$

For a mechanical prolongation of +20 mm, we measured on the RF-fingers without outer bellows mounted, an additional total electrical length of 18 mm, whereas on the RF-fingers with outer bellows mounted, we merely obtained 13 mm, i.e. a difference of 5 mm arises.

CONCLUSION

We present the measurement of a nested coaxial structure with the classical wire method in combination with the TDT method for high-Q resonances. The wire method was used here in spite of the well known rule that cavity-like modes should not be measured with wires since the high-Q resonances in the DUT are expected to be excited only in the outer volume between the bellows and the RF-fingers. As a consequence, these resonances from the outer volume couple only weakly to the inner part where the wire is placed and thus justify the use of the wire method. The use of probes, usually the standard method to determine high-Q resonances, would have required to drill a hole in the bellows in order to allow probe access and thus has been abandoned. From the TDT, it is possible to quantify through the determination of electrical delays, the effect of high-Q resonances that are driven by the beam-simulating wire. One limitation is that the linear regime for the phase response has to be maintained, i.e. the resonances shall ideally be sufficiently above the main frequency range of interest.

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