MODELING AND SIMULATION OF BROADBAND RF CAVITIES IN PSPICE

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Abstract

Barrier bucket systems are planned for the SIS100 Synchrotron (part of the future accelerator facility FAIR) and the ESR storage ring to facilitate several longitudinal beam manipulations [1] [2]. In order to achieve a single-sine gap signal of the desired amplitude and quality, effects in the linear and nonlinear region of the RF systems have to be investigated and included in the design of the overall system. Therefore, the cavities and the amplifier stages are to be modeled in PSpice. In this contribution, a cavity model will be presented. In a first step, a model for the magnetic alloy (MA) ring cores, which highly account for the properties of the cavity, has been found based on measurement data. In a second step, the future setup of the cavity is created using the MA ring core models. The model of the cavity allows simulations in frequency domain as well as time domain. The results show good agreement with former measurements.

INTRODUCTION

Barrier bucket systems can be used for a wide variety of longitudinal beam manipulation applications in synchrotrons (e.g. [3] [4] [5]). The main principle is to confine particles between two potential barriers which are generated by pulsed gap voltages (single sine pulses are considered here as a representative example). Between these barriers, the beam behaves like a coasting beam. One possible application is compression or decompression of the beam by changing the distance between the potential barriers (so called "moving barriers" [5] [6] [7]).

While a cavity system for accelerating particles produces a continuous sinusoidal signal of a certain frequency at the gap, a barrier bucket cavity system needs to provide pulsed signals of a certain waveform. As pulsed signals contain a wide range of different frequencies, each component of the system has to show broadband properties.

One way of reaching the desired broadband ability of the cavity is to use Magnetic Alloy (MA) ring cores for the coupling of the electromagnetic field, which is planned for the ESR and the SIS100 cavity. Hence, the first part of this contribution describes how the properties of the cores are measured and modeled in PSpice. The second part describes how the model of the overall setup of the ESR cavity, including coupling windings, the ceramic gap, parasitic capacitances and measurement devices, is made up. In the last part, measurements taken at a test setup are compared with simulation results in time and frequency domain.

MODELING OF MA RING CORES

The planned system is designed such that the ring cores are not driven into saturation. Therefore, the ring core can be modeled as a linear time invariant (LTI) system.

Measuring the Ring Core Properties

The impedance of the ring cores accounts for the main impedance of the later cavity and is therefore an important property for the design of the amplifier stage. As the measurement environment has significant influence on the measurement [8], a measurement setup (shown in Figure 1) has been built at GSI to shield the ring core from outer influences and to provide comparable conditions between different measurements.

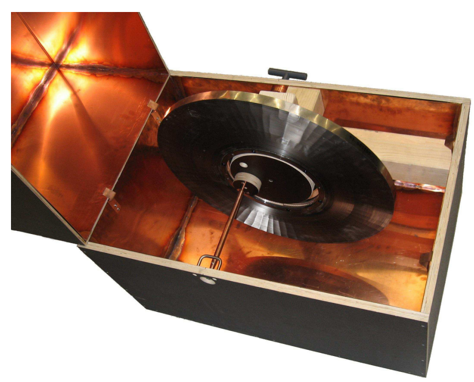

Figure 1: GSI setup for ring core measurements

Fitting of the Measurement Data

The impedance/admittance of a linear time invariant electric network can be described by a rational transfer function

$$\underline{H}(s) = \frac{\underline{A}(s)}{\underline{B}(s)} \tag{1}$$

where $\underline{A}$ and $\underline{B}$ are polynomials in s. Specifically, a vector fitting algorithm [9] [10] [11] is chosen, which produces a fit function of the form

$$f(s) = \sum_{i=1}^{N} \frac{r_i}{s - p_i} + d + se. \tag{2}$$

with residues r_i and poles p_i and real-valued elements d and e. Equation (1) can be transformed into the form of equation (2) by partial fraction decomposition.

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Finding an RLC Circuit for the Ring Core

Once a fitting function of the form (2) is found, an equivalent circuit can be built [12]. As the fit represents an admittance, the different summands will be represented by parallel branches. Figure 2 shows the resulting circuit of the fit.

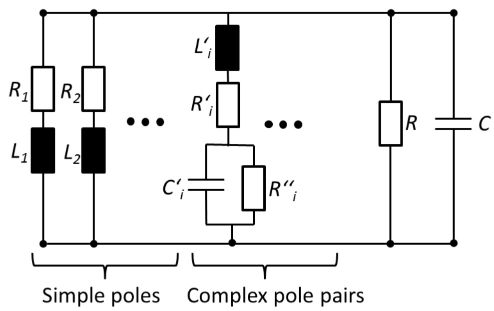

Figure 2: RLC equivalent circuit for the fit function

The admittance of this circuit can be described by

$$Y(s) = \sum_{i=1}^{N} \frac{\frac{1}{L_i}}{s + \frac{R_i}{L_i}} + \frac{1}{R} + sC \tag{3}$$

which has the same form as (2). R_i, L_i, R and C are the lumped elements shown in Figure 2. Thus, the numerical values of the circuit elements can directly be extracted from the fit function[1]. This equivalent circuit will represent the ring core in further PSpice simulations. Figure 3 shows the measured admittance and the fit. For the specific ring core considered here (Hitachi FT-3M [13] [14]), the deviation of the imaginary part at high frequencies results in a phase deviation of 12° at 30 MHz, while the amplitude differs by less than five percent.

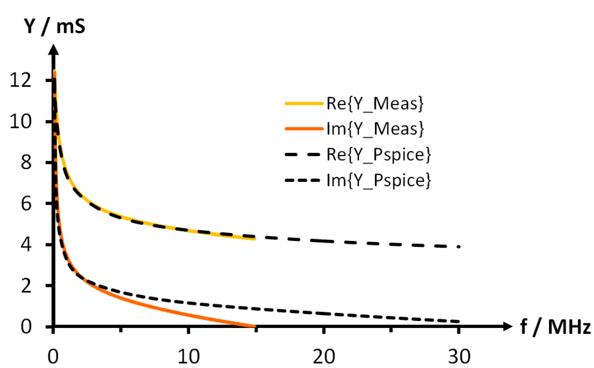

Figure 3: Comparison of measurement and fit function for the admittance of one ring core

FULL MODEL OF THE ESR BARRIER BUCKET CAVITY

The final cavity will consist of two halves of four ring cores each as shown in Figure 4. Via these cores connected in parallel, the desired voltage will be induced to the two gaps.

In the PSpice model, the coupling of the signal to the beam pipe via the ring cores is realised by a parallel circuit of the ring core models and ideal couplers. As the distance between the windings and the grounded housing of the cavity is comparatively big, the main part of the stray capacity between the winding and ground is located at the feedthrough at the coupling input. Therefore, the stray capacitance is modelled by one concentrated capacitance at the beginning of the coupling. The value has been measured with open ended windings at the test setup. The gaps are modeled by a concentrated capacitance as well. The

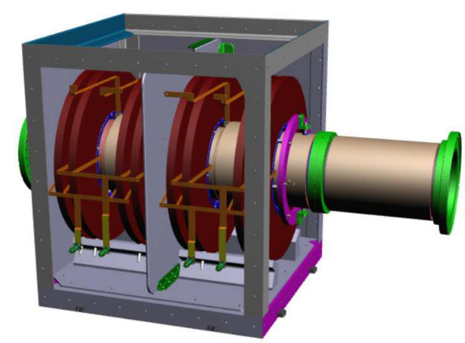

Figure 4: CAD model of the ESR cavity

PSpice model of the cavity is shown in Figure 5. Besides the cavity, a two-channel signal generator of the test setup is modeled by a voltage source and two 50 Ω output resistances. A PSpice standard cable model is chosen for 50 Ω coaxial cables in the test setup and input ports of oscilloscopes are modeled by the chosen input impedance (50 Ω or 1 MΩ) in parallel with a capacitance of 18 pF according to the data sheet.

SIMULATION RESULTS

The current method for the single-sine pulse generation is a Fourier analysis of the system [15]. The spectrum of the desired output voltage at the gap of the cavity can be described by a Fourier series [16]

$$U(t) = \mathrm{Re}\left\{ \sum_{k=1}^{\infty} \underline{c}_k e^{jk\omega t} \right\} \tag{4}$$

with the complex Fourier coefficients [17]

$$\underline{c}_k = \frac{\hat{U}\tau}{2T_{BB}} \left[\mathrm{si}\left(k\pi\left(1 + \frac{\tau}{T_{BB}}\right)\right) - \mathrm{si}\left(k\pi\left(1 - \frac{\tau}{T_{BB}}\right)\right)\right]. \tag{5}$$

with period T_{BB} and pulse length τ. As one can see in formula (4), the signal contains an infinite number of discrete harmonic frequencies, which is why the broadband ability of the system is essential for the signal generation. The input signal is determined by measuring the transfer function $\underline{H}(\omega)$. This is done by a frequency sweep of a sinusoidal

[1] If complex pole pairs occur, the RL-branch needs to be expanded by the RC part in Figure 2.

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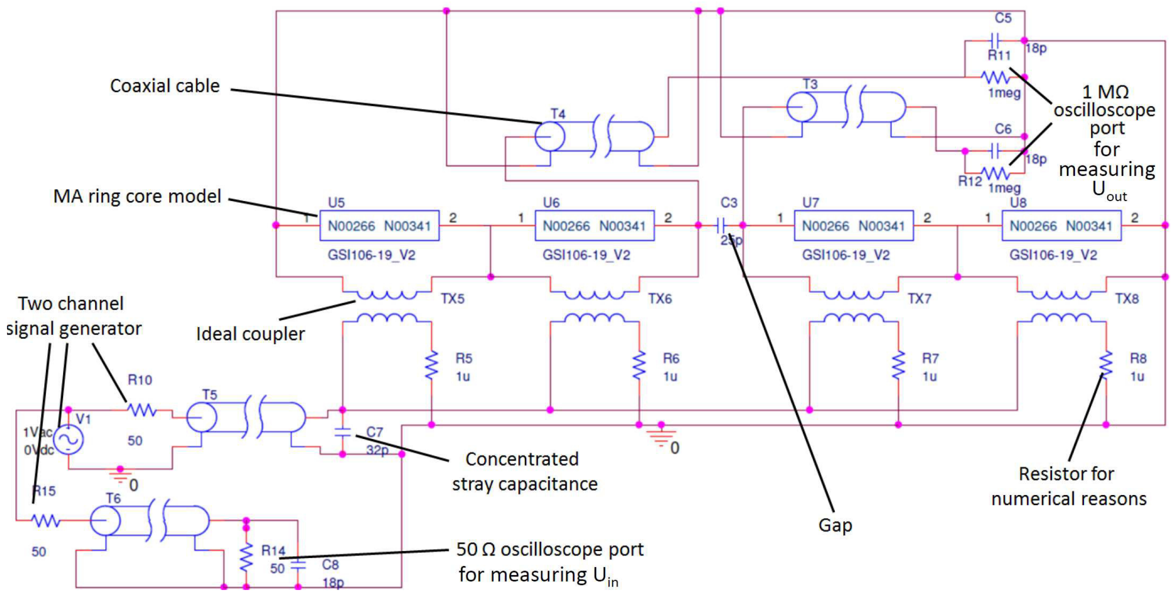

Figure 5: PSpice model of the actual test setup of half the ESR cavity at GSI including measurement devices and cables

signal at the signal generator and the simultaneous measurement of the gap voltage. With the measured transfer function, the frequency components $\underline{c}_{k,in}$ of the input signal can be determined from the transfer function and the frequency components of the output signal $\underline{c}_{k,out}$ by

$$\underline{c}_{k,in} = \frac{\underline{c}_{k,out}}{\underline{H}(\omega_k)} \tag{6}$$

with $\omega_k = 2\pi k f_0$. In order to analyze the performance of the cavity model, a reduced system containing the signal generator and one half of the cavity only is used as test setup and in simulation.

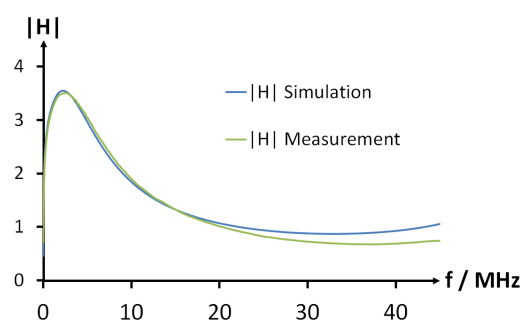

Figure 6: Simulated and measured transfer function for the whole system including cavity and signal generator

As ring core measurements were taken up to a frequency of 30 MHz only, the comparison between simulation and measurement is done by performing Fourier analysis in the same range. However, one can see in Figure 6 that the transfer function of the model's characteristics are similar to measurements up to a frequency of about 45 MHz.

In Figure 7, the calculated input signals based on the transfer functions gained from measurement and from simulation are shown. Since the transfer functions are similar, the input signals only show small differences. The gap signal is close to a pure single-sine signal, but as all frequency

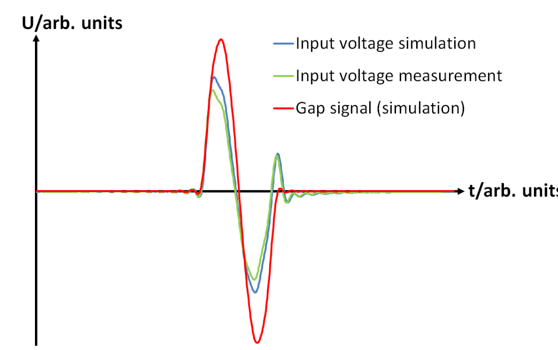

Figure 7: Input signals and resulting gap voltage

components above 30 MHz are missing, it shows small oscillations before and after the pulse. The quality of the signal can be improved by the inclusion of higher frequency components into the calculation of the input signal.

CONCLUSION

The presented PSpice model shows a way to systematically create a model of a full MA cavity from measured MA ring core and stray capacitance data. No other lumped element components were needed to improve the simulation results. The model shows good agreement with measurements taken at a test setup at GSI in time and frequency domain and enables the simulation of barrier bucket signal generation.

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