DESIGN OF A COMPUTER BASED RESONATOR-SIMULATOR FOR TESTS OF RF CONTROL SYSTEMS[*]

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Abstract

In order to test RF control systems for accelerator cavities without being dependent on available prototypes, a resonator-simulator has been developed. The Simulator is based on a Xilinx VIRTEX-4 FPGA module and has been configured using MATLAB Simulink with a special Xilinx blockset. The underlying model for this configuration is a parallel RLC circuit that has been parameterised with common RF quantities like the resonance frequency, driving frequency, bandwidth and quality factor. This approach allows the behaviour of normal conducting cavities with quality factors up to 10^4 as well as superconducting cavities with quality factors up to 10^9 to be simulated. Besides, it can be operated in continuous-wave mode as well as in pulsed mode. We report on the mathematical model, its digital representation and on the benchmarking against realistic cavity behaviour.

INTRODUCTION

For experiments with intense antiproton beams, a dedicated proton LINAC is foreseen as an injector for the future Facility for Antiproton and Ion Research (FAIR). The proposed scheme with normal conducting crossed-bar H-mode cavities operated in a pulsed mode is planned to feed directly into the heavy-ion synchrotron SIS18 of the present GSI Helmholtz center for heavy-ion research [1]. The corresponding digital radio frequency control system for a test-bench setup is currently being developed at TU Darmstadt [2]. Due to the fact that there are no cavity prototypes available, a cavity simulator has been developed. This device is able to simulate normal conducting as well as superconducting cavities with common physical effects like beam loading, amplifier saturation and Lorentz-force detuning (LFD). In consequence of its ability to simulate superconducting cavities it also can be used to improve the digital control system [3] of the Darmstadt electron LINAC S-DALINAC [4] without being dependent on an available superconducting resonator or RF periphery.

THE RESONATOR MODEL

The simulator is based on a resonator model consisting of a parallel circuit of a resistor R, an impedance L and a capacity C that is driven by a generator current I_{gen} as shown in Fig. 1. The corresponding differential equation describing the voltage reads:

$$\ddot{U} + \frac{1}{RC}\,\dot{U} + \frac{1}{LC}\,U = \frac{1}{C}\,\dot{I}_{\text{gen}} \qquad (1)$$
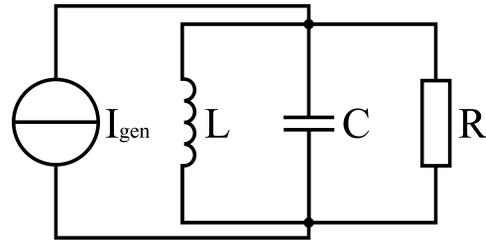
Figure 1: The equivalent circuit representing the cavity

It is convenient to rewrite this equation with more common RF parameters like the resonance frequency ω_r, the quality factor Q and the half width at half maximum $\Delta\omega_{1/2}$. With these the equation reads:

$$\ddot{U} + \frac{\omega_r}{Q_L}\,\dot{U} + \omega_r^2\,U = \frac{\omega_r}{Q_L}\,\dot{U}_{\text{gen}} \qquad (2)$$

To solve Eq. (2) one can use Eq. (3) as an ansatz which is motivated by the in-phase and quadrature procedure commonly used with RF control systems. The in-phase signal is denoted by V, while W represents the quadrature component.

$$U(t) = (V + iW) \cdot e^{i\omega t} \qquad (3)$$

Time discretisation and the introduction of several approximations (details described, e.g., in [5]) lead to:

$$V(t+\Delta t) = V(t) + \left[\omega_{1/2}\,(V_{\text{gen}} - V(t)) - \Delta\omega W\right]\Delta t$$
$$W(t+\Delta t) = W(t) + \left[\omega_{1/2}\,(W_{\text{gen}} - W(t)) + \Delta\omega V\right]\Delta t$$

HARDWARE

The simulator has been implemented on an Lyrtech VHS-ADAC board providing 8 DAC and 8 ADC channels with a resolution of 14 bit and a Xilinx VIRTEX-4 FPGA-module. The latter has been configured using the "Xilinx System Generator for DSP" [6] library for MATLAB/Simulink. This software package allows the designer to generate high-performance HDL code directly from the Simulink interface using pre-optimized algorithms for the Xilinx hardware. Using this tool greatly simplifies the configuration of the FPGA.

COMPARISON TO A REAL RESONATOR

A pulsed control system has to be able to tune the cavity's electrical field magnitude and phase to the wanted value as fast as possible. During this process it reacts on fast changes of these quantities. So for the simulator it is very crucial to reproduce the transient response of a real cavity with high precision.

On account of this the step-function response has been measured for the simulator and for a normal conducting pre-buncher with RF parameters shown in Table 1. The measurement was performed with resonant excitation as well as with non-resonant excitation by detuning the input signal by the amount of a full width at half maximum of the cavity. The results are shown in Figs. 2 and 3. For the shown dataset the resonantly excited curve holds an RMS error of $\Delta_{\mathrm{RMS}} = 6.9 \cdot 10^{-3}$ while the set with non-resonant excitation exhibits an error of $\Delta_{\mathrm{RMS}} = 4.02 \cdot 10^{-2}$. The latter error mainly results from the first μs.

Table 1: RF Parameters of the Prebuncher Used for the Comparison Measurement

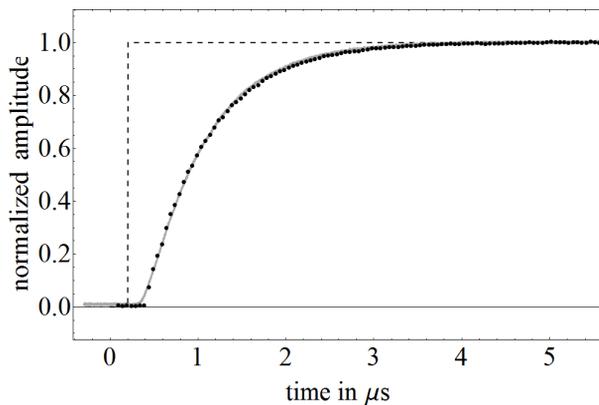| Resonance frequency	(2994.1 ± 0.475) MHz
Bandwitdth (FWHM)	(475 ± 20) kHz
Loaded quality factor Q_L	6300 ± 265

Figure 2: Response of the simulator (dotted) and a real cavity (gray) for resonant excitation by a step function (dashed)
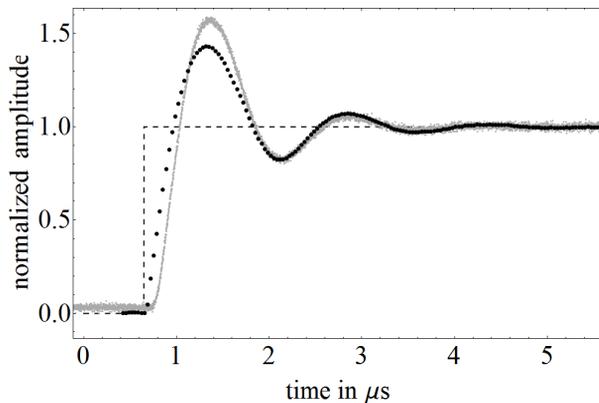

Figure 3: Response of the simulator (dotted) and a real cavity (gray) for non-resonant excitation following a step function (dashed). The used input signal was detuned by $\Delta f = \Delta f_{\mathrm{FWHM}}$ with Δf_{FWHM} denoting the full width at half maximum of the resonance centroid.

AMPLIFIER SATURATION

When RF amplifiers are operated near their maximum output level, most of them show a certain amout of saturation. This means the output characteristics is non-linear for high output levels. Hence, the control path for the control system also becomes non-linear. This has to be taken into account while developing new control systems. Therefore the simulator was implemented to reproduce this behaviour, too. It is possible to enter a four-point approximation of a known saturation curve into the simulator. The approximation is then used to transform the output of the simulator. The level of accuracy for the approximation, i.e., the number of points describing the output characteristics of the amplifier, is limited by the hardware of the simulator.

BEAM LOADING

A beam of charged particles traveling through a cavity interacts with the electro-magnetic field inside and converts field energy into kinetic energy. As the field amplitude inside the cavity decreases, the control system is in charge to increase the input power fast enough to prevent the amplitude from dropping significantly.

To be able to test this beam-loading effect with the simulator, an additional current source that has an opposite sign compared to the generator-current source, while sharing the same phase, is introduced. The length, period and delay of the virtual particle beam is determined by an internal counter. To achieve synchronisation between the external generator current and the internal beam counter, a trigger input port is used to reset the counter periodically. Figure 4 shows a result of the simulator inducing a beam-loading effect.
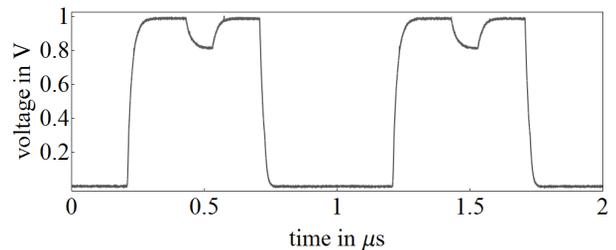

Figure 4: Output voltage of the simulator with beam loading

LORENTZ-FORCE DETUNING

For the simulation of superconducting cavities the transient response is less important, due to their high quality factor and slow step response. The small bandwidths, on the other hand, favour problems that affect the resonance frequency. For the mechanically rather unstable superconducting cavities any stress results in a relevant shift of the resonant frequency. Even the induced electromagnetic field deforms the geometry of the resonator and shifts the resonance frequency by a significant amount.

This Lorentz-force detuning is a current problem in accelerator physics [7]. The simulator uses the fact that LFD shifts the resonance frequency proportional to the square of the electric field amplitude in the cavity:

$$\Delta\omega_{\text{LFD}} = -2\pi \cdot K \cdot E_{\text{acc}}^2 \tag{4}$$

The factor K represents a constant of proportionality called "Lorentz-force-detuning constant". With the informations from Eq. (4) the simulator is able to reproduce this effect as shown in Fig. 5.
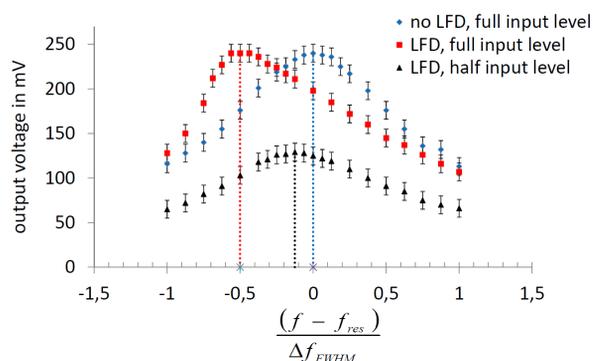

Figure 5: Measurement of the frequency shift due to LFD. The output voltage is shown as a function of the relative frequency, for the maximum amplitude input (squares) and half of the maximum amplitude (triangles). For comparison, the resonator resonance curve without LFD is indicated by diamond symbols.

GUI

The Xilinx System Generator for DSP provides the opportunity to communicate with the FPGA via Simulink. This allows the designer to create a graphical user interface, that simplifies the use of the simulator drastically. The current version of the GUI allows to enter the resonance frequency of the simulator, the parameters of the virtual beam like its length, period and magnitude and the Lorentz-force-detuning constant. Furthermore the GUI allows the user to read out some of the internal parameters of the simulator like the current resonance frequency, and the current frequency detuning.

CONCLUSION

The developed flexible cavity simulator is able to simulate normal conducting cavities as well as superconducting cavities. In both cases it is able to simulate relevant physical effects known from practical experience. The simulator can be used to easily test or improve control systems, without being dependent on RF or cryogenic equipment. In addition to that the strength of the simulated effects can be varied over a great range which would be difficult in reality. Furthermore the usage is easy and intuitive.

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