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DEVELOPMENT OF AN FPGA-BASED CAVITY SIMULATOR FOR TESTING RF CONTROLS

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DEVELOPMENT OF AN FPGA-BASED CAVITY SIMULATOR FOR TESTING RF CONTROLS

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Abstract

LLRF is used to precisely control the amplitude and phase of the RF field in cavities. Often times, access to test the control algorithms with RF equipment, especially in the presence of beam, is limited or beyond reach. In such cases, testing must be done through computer modeling or simulations. Computer modeling is often too slow and difficult to interface with the LLRF hardware. Analog or digital cavity simulators are preferred as they allow for interaction with the LLRF controls platform in real-time, and compared to their analog counterparts, FPGA-based digital cavity simulators allow for a more adjustable and sophisticated implementation. The newly developed FPGA-based cavity simulator includes the cavity electrical model, the cavity mechanical model including Lorentz Force Detuning and microphonics, an amplifier model which can simulate real amplifier nonlinearities, and a beam model. The simulator has been validated using measurements from BNL's CeC 704 MHz 5-cell SRF cryomodule.

INTRODUCTION

The cavity simulator described in this paper was originally inspired by [1] and [2] both of whom also implemented FPGA-based simulators.

This paper first discusses the physics background that is relevant to the models implemented in the simulator. This includes the cavity electrical and mechanical model, the beam model, and the amplifier model. Next, the paper will discuss how the various components of the cavity simulator were tested, specifically, using data from real measurements with cavities. Lastly, the paper will conclude with the current status of the cavity simulator and any remaining work.

PHYSICS BACKGROUND

In this section, the following approximation for the time derivative of a signal will be used:

$$\dot{x} \approx \frac{x[n] - x[n-1]}{T_s} \tag{1}$$

This approximation holds because the sampling period used is 50 ns. The simulator is implemented on a Xilinx Vertix-5 FPGA.

Electrical Model

The cavity electrical model can be described as a RLC circuit, mathematically, the cavity voltage is described by the following second-order differential equation:

$$\ddot{V}_C + \frac{\omega_0}{Q_L}\dot{V}_C + ({\omega_0}^2)V_C = \omega_0^2(\frac{2\beta}{1+\beta}V_f + R_L I_b) \tag{2}$$

Where V_C is the cavity voltage, ω_0 is the resonant frequency, Q_L is the loaded Q, β is the coupling factor between the amplifier and cavity, V_f is the forward voltage, R_L is the loaded resistance, and I_b is the DC beam current.

Using the approximation described in [3] and by applying (1), equation (2) can be simplified into the following form:

$$\begin{bmatrix} V_{C_I}[n] \\ V_{C_Q}[n] \end{bmatrix} = \begin{bmatrix} 1 - T_s\omega_{1/2} & -T_s\Delta\omega \\ -T_s\Delta\omega & 1 - T_s\omega_{1/2} \end{bmatrix} \begin{bmatrix} V_{C_I}[n-1] \\ V_{C_Q}[n-1] \end{bmatrix} + T_s\omega_{1/2}\vec{u}[n] \tag{3}$$

These discrete equations can be implemented on the FPGA. If we assume no detuning, it can be seen that the IQ data is decoupled and the cavity electrical model is simply a lowpass filter at baseband. Also, it's interesting to note that the cavity electrical model is implemented as a complex filter (it takes both I and Q as inputs) due to the asymmetric response of the cavity at RF.

Mechanical Model

According to [4], the cavities mechanical model can be represented as a superposition of various resonant mechanical modes. Specifically, the k'th mechanical mode can be represented using the following differential equation:

$$\Delta\ddot{\omega}_k + (\frac{\omega_k}{Q_k})\Delta\dot{\omega}_k + \omega_k^2\Delta\omega_k = -\omega_k^2 K_k E_{acc}^2 - \phi_{microphonics} \tag{4}$$

Where $\Delta\omega_k$ is the cavity detuning due to the k'th mechanical mode, ω_k is the k'th resonant frequency, Q_k is the Q of the k'th mode, K_k is the Lorentz Force Detuning constant for the k'th mode, and E_{acc} is the accelerating gradient.

Previously, the cavity electrical model (which is also a resonant mode) was approximated as a complex lowpass filter at baseband. The reason such an approximation could be made is because the bandwidth of the system (< 150 kHz) is much smaller than the RF frequency [3]. However, for the mechanical modes, the resonant frequencies are already very small (< 500 Hz) so such an approximation cannot be made.

Instead, the second order differential equation is broken up into 2 first order differential equations. Let $x_1 = \Delta\omega_k$ and $x_2 = \Delta\dot{\omega}_k$. Then:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -(\frac{\omega_k}{Q_k})x_2 - \omega_k^2 x_1 - (\omega_k^2 K_k E_{acc}^2 + \phi_{microphonics})$$

Then, eq (1) can be applied to the equations above and those discretized equations can be directly implemented on an FPGA.

The microphonics were modeled using a linear feedback shift register [5] which can generate pseudo-random bits.

Amplifier Model

An amplifier model is created to try to account for the frequency response of the amplifier and non-linearity due to saturation. The frequency response of the amplifier is modeled using a lowpass filter with some programmable cutoff frequency. To model non-linearity, this cavity simulator uses the same method as described in [6]. First, power sweeps are taken on real amplifiers to measure the amplitude and phase non-linearity, this information is stored in a LUT. Then, the filtered IQ data is fed into a CORDIC to obtain the magnitude which is used to index the LUT. The LUT outputs are used to modulate the IQ data stream.

Beam Model

Ideally, the beam would be modeled using Gaussian pulses on the FPGA. However, due to the high sampling rates required to recreate these pulses, a DC beam model is instead used. Therefore, the beam is modeled using periodic rectangular pulses, with the period being equal to the revolution period of the machine. The duty cycle of these pulses can be adjusted to represent how many buckets are occupied. The user can set the revolution period, duty cycle, beam current, and beam phase.

Complete Simulator

The individual components can now be combined and the result is shown in Figure 1.

HARDWARE IMPLEMENTATION AND VALIDATION

The simulator was implemented using hardware from a development field control chassis here at BNL. The field control chassis provides the necessary hardware (ADCs and DACs) as well as a connection to controls software which can be used to configure the simulator. To drive the simulator, another development chassis was used which makes it easy to recreate setups from RHIC, AGS, CeC, etc. as they all use similar hardware and the same controls software.

The simulator was validated using historical data from the 704 MHz SRF cavity used for CeC here at BNL. First, the controls setup was recreated in the chassis used to drive the simulator. Then, using the same settings as were used in CeC, the simulator is driven in pulsed mode. Below, a comparison of the real data (blue) and the cavity simulator output (orange) is shown. As can be seen, the cavity, forward, and reverse signals match very closely:

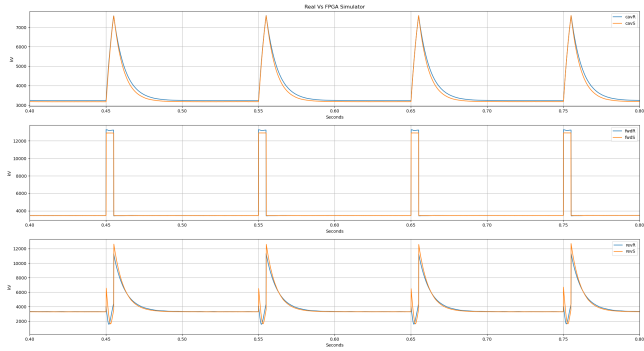

Figure 2: Pulsed Mode Comparison of Real Data (Blue) and Cavity Simulator (Orange)

The mechanical model of the cavity simulator was validated by comparing PLL data of detuning in the 704 MHz cavity during pulsed operation. First, the detuning data is used to obtain the coefficients needed for the mechanical model. This is done by applying the cavity voltage signal, obtained from the real data, to a model of 4 mechanical modes to obtain simulated detuning data. Then, a fit is preformed to determine the coefficients of the mechanical modes. Mathematically, the following loss function is minimized:

$$\mathcal{L} = |\Delta\omega_{real} - H_{mech}(y)|^2$$

Once the coefficients are determined, they are applied to the cavity simulator's mechanical model. Below, PLL data of detuning from the real setup (blue) is compared to the detuning of the cavity simulator (orange):

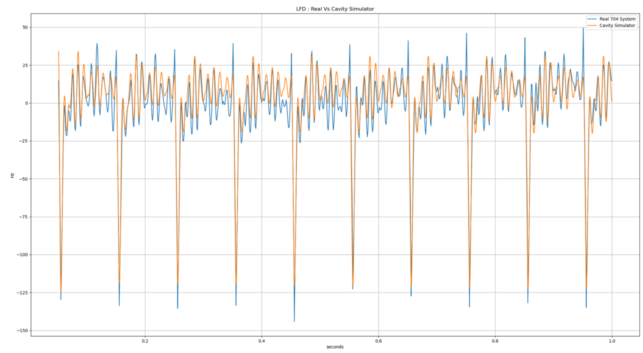

Figure 3: PLL data of Real Data (Blue) and Cavity Simulator (Orange)

CONCLUSION

There still remains work to do on the cavity simulator. For one, there are multiple models that are not currently incorporated which would be useful to have. For example, having a fast analog feedback on the FPGA, also a tuner model (motor or ferrite) would allow users to test a wide array of algorithms. Having a tuner model would also allow for the implementation of cavity detuning in response to reactive beam loading. Besides the missing models, there still remains work with regard to optimizing the simulator.

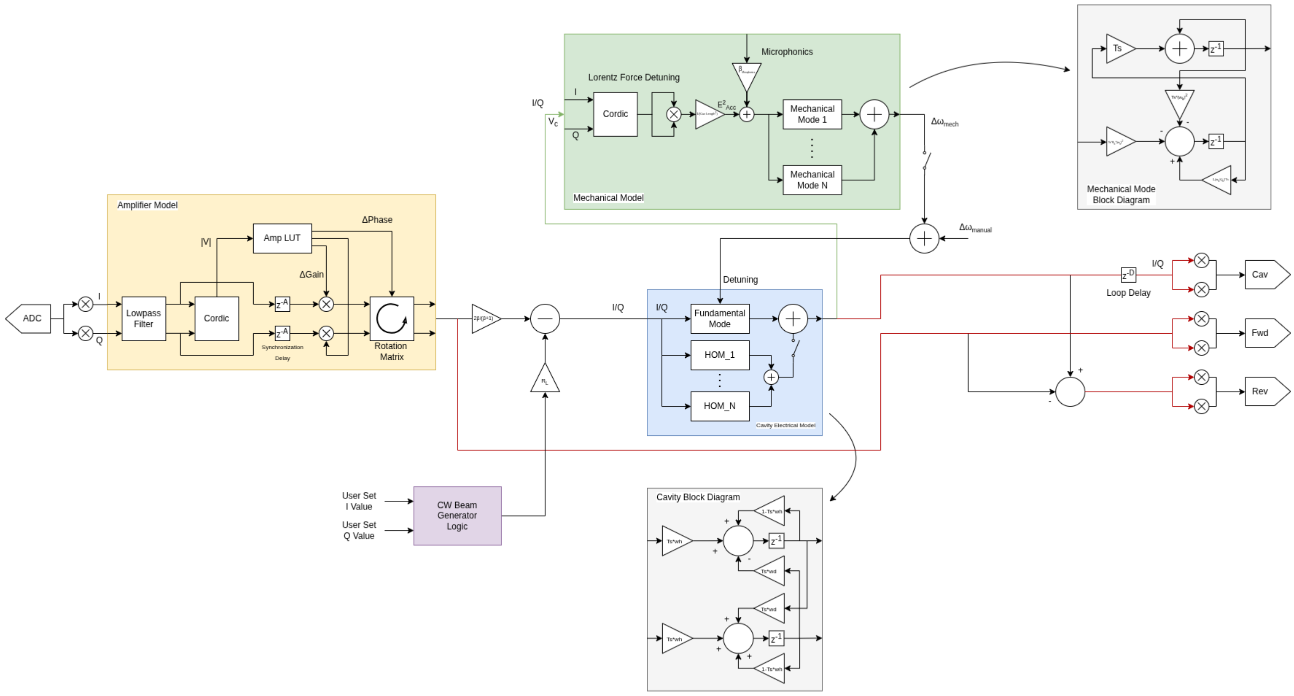

Figure 1: Block Diagram Of Cavity Simulator

Currently, the code is not ideal and there is a significant delay through the simulator. Also, the delay through the mechanical model can result in cavity detuning that is inaccurate even though the coefficients are correct. Furthermore, while the linear feedback shift register implementation of microphonics works in simulations, on the FPGA it is a different story and fails to produce any detuning.

Despite the work that remains, the implementations of the cavity electrical model, the beam model, and especially the cavity mechanical model have proved useful for testing new algorithms or hardware. As LLRF work for the EIC procedes, the flexibility of the FPGA based cavity simulator is especially nice for testing the wide range new systems. For those who are interested in the code, feel free to reach out to the email listed at the top of the paper.

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