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SRF CAVITY SIMULATOR FOR LLRF ALGORITHMS DEBUGGING*

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Abstract

The availability of niobium superconducting cavities, either due to a lack of a real cavity or due to the time needed for the experiment set up (vacuum, cryogenics, cabling, etc.), is limited, and thus it can block or delay the development of new algorithms such as low level RF control. Hardware-in-the-loop simulations, where an actual cavity is replaced by an electronics system, can help to solve this issue. In this paper we present a Cavity Simulator implemented in a National Instruments PXI equipped with an FPGA module. This module operates with one intermediate frequency input which is IQ-demodulated and fed to the electrical cavity's model, where the transmitted and reflected voltages are calculated and IQ-modulated to generate two intermediate frequency outputs. Some more advanced features such as mechanical vibration modes driven by Lorentz-force detuning or external microphonics have also been implemented. This Cavity Simulator is planned to be connected to an mTCA chassis to close the loop with a LLRF control system.

ELECTRICAL MODEL

An equivalent electric circuit can be used to model a superconducting cavity, [1], where the power amplifier and beam are represented as current generators, the fundamental power coupler as a transformer and the cavity as an RLC-circuit. Figure 1 shows the equivalent circuit of the fundamental mode of a cavity connected to an RF power source, where V_{cav} represents the transmitted voltage to the cavity, V_{ref} the reflected voltage sent to the circulator in order to protect the RF power source, and the circuit components are defined in terms of the cavity parameters:

$$\sqrt{\frac{L}{C}} = \frac{R}{Q} \tag{1}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{2}$$

$$\frac{R}{Q} = \frac{R_{sh}}{Q_0} = \frac{2R}{Q_0} \tag{3}$$

where R_{sh} is the shunt impedance used in accelerator physics. The ratio of the transformer depends on the coupling of the cavity β, $m = \sqrt{\frac{R}{\beta Z_0}}$. The envelope of the RF transmitted voltage in the cavity can then described by the differential equation (4) where $\omega_{1/2} = \frac{\omega_0}{2Q_L}$, $R_{\text{L}} = \frac{R}{1+\beta}$, $\Delta\omega$ the cavity detuning and $\boldsymbol{V}_{\text{cav}} = \left(V_{\text{cav}}{}^{r}, V_{\text{cav}}{}^{i}\right)$, $\boldsymbol{I}_{\text{amp}} = \left(I_{\text{amp}}{}^{r}, I_{\text{amp}}{}^{i}\right)$ are the real and imaginary parts of cavity voltage and the driven current respectively.

$$\frac{d}{dt}\boldsymbol{V}_{\text{cav}} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \boldsymbol{V}_{\text{cav}} + \\ + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \frac{\boldsymbol{I}_{\text{amp}}}{m} \tag{4}$$

The reflected voltage is calculated with the following equation:

$$\boldsymbol{V}_{\text{ref}} = \frac{\boldsymbol{V}_{\text{cav}}}{m} - \frac{Z_0 \boldsymbol{I}_{\text{amp}}}{2} \tag{5}$$

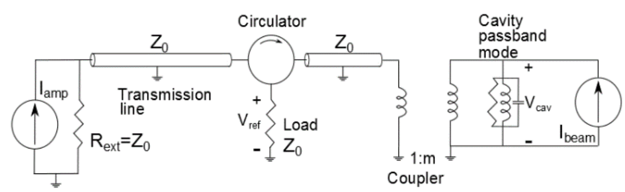

Figure 1: Electrical equivalent circuit of a superconducting cavity.

MECHANICAL MODEL

Coupled to the electrical response, superconducting cavities present also a mechanical response as the system composed by the superconducting cavity, the helium vessel and the tuner forms a mechanical structure with characteristic vibration eigenmodes. Im For the Lorentz force scenario, the detuning produced by one of the mechanical eigenmodes is given by the following equation:

$$\frac{d}{dt}\begin{pmatrix} \Delta\omega_m(t) \\ \Delta\dot{\omega}_m(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\omega_m{}^2 & \frac{\omega_m}{Q_m} \end{pmatrix} \begin{pmatrix} \Delta\omega_m(t) \\ \Delta\dot{\omega}_m(t) \end{pmatrix} + \\ + \begin{pmatrix} 0 \\ -K_m\omega_m{}^2 \end{pmatrix} E_{\text{cav}}{}^2 \tag{6}$$

where $\Delta\omega_m(t)$ is the detuning caused by the mechanical eigenmode, ω_m, Q_m, and K_m are respectively the natural frequency, the quality factor and coupling factor of the driven force of the eigenmode, and E_{cav} is the electric field in the cavity, [2]. When the detuning is caused by external microphonics the detuning is described by a similar equation.

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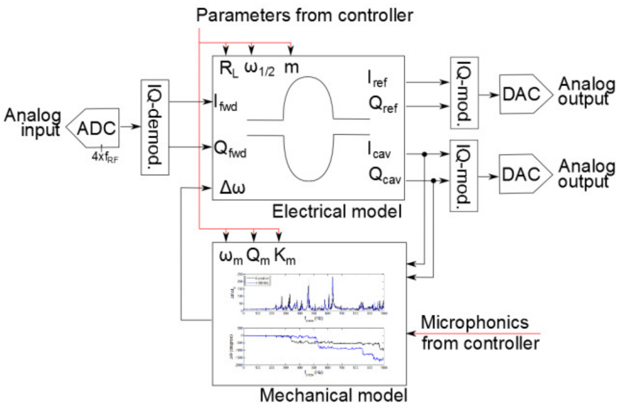

Figure 2: Block diagram of the implementation.

IMPLEMENTATION AND RESULTS

The hardware implementation was done using a commercial off-the-shelf device by National Instruments which consists on a PXIe chassis [3], a chassis controller running Windows [4], an FPGA module [5] and an analog adapter module [6].

Figure 2 shows the block diagram of the implementation. Discretized versions of equations (4), (5) and (6) are implemented in the FPGA module and get all the necessary parameters from the Windows controller through the backplane. This parameters are introduced by the user via a Graphical User Interface (GUI).

In order to calculate the In-Phase (I) and In-Quadrature (Q) components the IQ-demodulation technique has been chosen where the sampling frequency (100 MHz maximum) has to be four times higher than the RF input. Calculated transmitted and reflected voltages are IQ-modulated, converted to analog and sent to the analog module outputs.

The input of the mechanical model can be chosen to be the cavity voltage to emulate the Lorentz force detuning or a microphonics signal coming from the Windows controller. Up to now this signal can only be a step input to simulate the gas bubbles kicking as seen in [7] but it is foreseen to include actual recorded microphonics.

In order to test the behavior of the implementation a signal generator operated in pulsed mode at 25MHz was connected to the analog input and a second generator synchronized with the first one operating at 100MHz was connected to the clock input. The resulting transmitted and reflected voltages for different cavity parameters, introduced in the GUI, are connected to an oscilloscope to check the pulsed behavior of the simulator. Table 1 show the comparison between theoretical and measured fall times and theoretical and measured maximum transmitted voltages for a given input level and for different Q_{ext}. It can be seen that there is a good match between both. In Figs. 3 and 4, the transmitted and reflected voltage respectively of a critical coupled cavity can be seen. The behavior of the reflected voltage for the three possible situations regarding the coupling (overcoupled, critically coupled and undercoupled) matches with the theoretical predicted behavior, [8].

Table 1: Measured and theoretical fall time and maximum voltage depending on Q_{ext} for $Q_0 = 5\times10^{10}$, $\frac{r}{Q} =$ 1000 ohm, $\Delta f = 0$, and $f_{RF} = 1.3$ GHz.

Q_{ext}	t_{fall}		V_{cav}^{max}	
	Meas.	**Theo.**	**Meas.**	**Theo.**
5×10^6	1.13 ms	1.22 ms	2.66 MV	2.68 MV
5×10^7	12.0 ms	12.23 ms	8.22 MV	8.48 MV
5×10^8	117 ms	121.2 ms	25.46 MV	26.57 MV
5×10^{10}	5.9 s	6.12 s	66.84 MV	68.04 MV

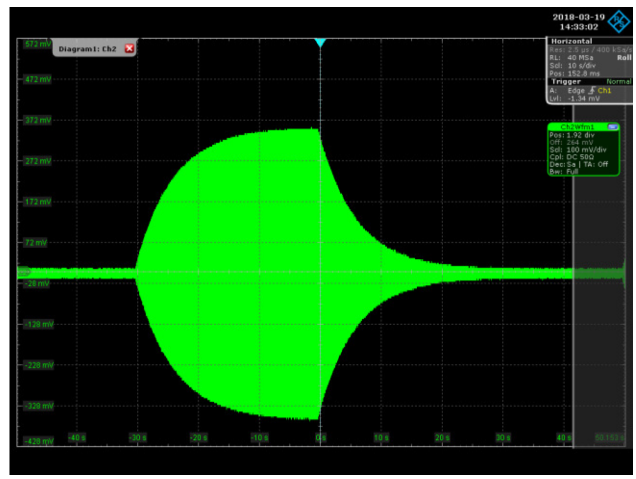

Figure 3: Transmitted voltage for $Q_{\mathrm{ext}} = Q_0 = 5\times10^{10}$, $\frac{r}{Q} = 1000$ ohm, $\Delta f = 0$, $f_{\mathrm{RF}} = 1.3$ GHz, and a pulse length of 30 s. The frequency of the signal is 25 MHz.

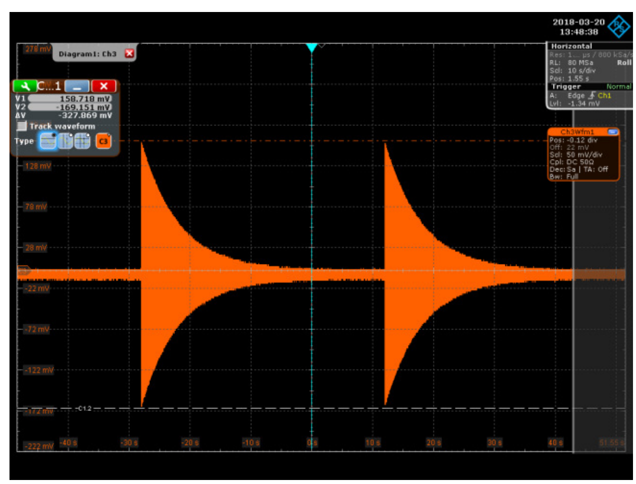

Figure 4: Reflected voltage for $Q_{\mathrm{ext}} = Q_0 = 5\times10^{10}$, $\frac{r}{Q} =$ 1000 ohm, $\Delta f = 0$, $f_{\mathrm{RF}} = 1.3$ GHz, and a pulse length of 40 s. The frequency of the signal is 25 MHz. The peaks at the beginning and end of the pulse have the same height as it is a critical coupled cavity.

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The available resources of the FPGA allow the implementation of up to five mechanical eigenmodes that can be driven by the square of the amplitude of the field in the cavity or by step-wise microphonics coming from the Windows controller. Figure 5 shows how one mechanical mode at 50 Hz is excited due to the Lorentz force detuning in pulsed operation mode. Figure 6 depicts the step-wise detuning caused by microphonics driving five mechanical eigenmodes.

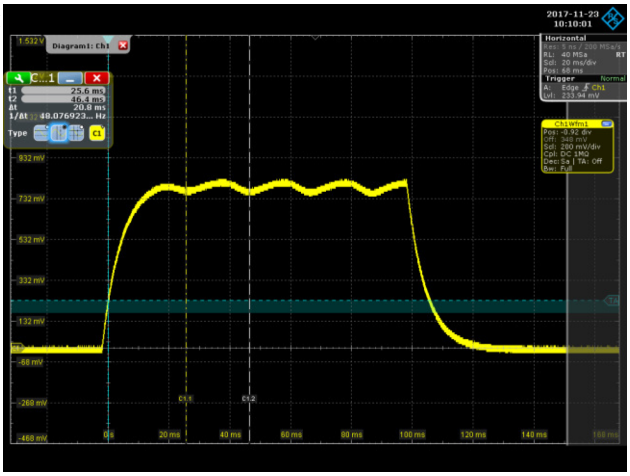

Figure 5: Effect of the Lorentz force detuning coupled with a 50Hz mechanical mode in the amplitude in a cavity with $Q_0 = 5 \times 10^{10}$, $Q_{\text{ext}} = 5 \times 10^7$, and $f_{RF} = 1.3$ GHz.

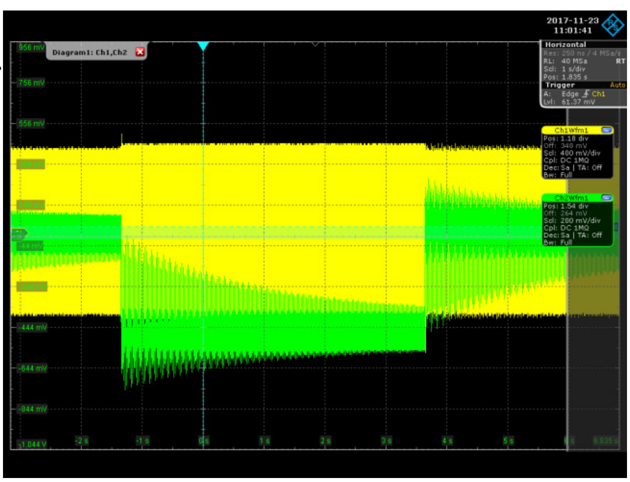

Figure 6: Step-wise detuning caused by microphonics driving five mechanical eigenmodes (green) and its effect on the transmitted voltage (yellow).

DEBUGGING OF LLRF ALGORITHMS

The purpose of this cavity simulator is, among others, to facilitate the debug of LLRF algorithms before they are used in an actual SRF cavity. In order to connect the simulator to the mTCA electronics that will be used for the bERLinPro LLRF control, and up/down converter has to be used to match the frequencies. Figure 7 shows the set up that has been connected to an mTCA chassis to debug a Kalman filter to estimate the detuning of an SRF cavity, [9].

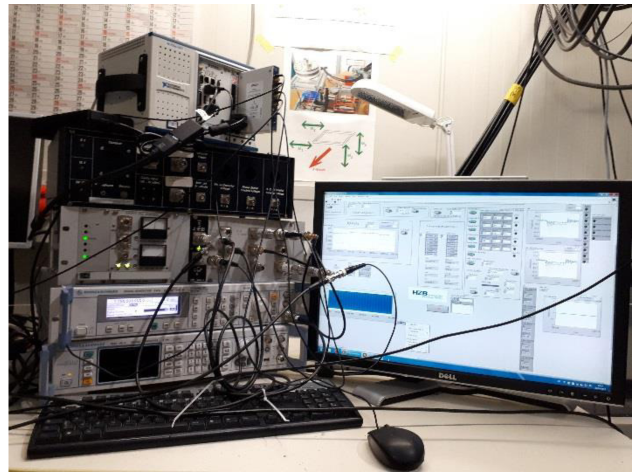

Figure 7: PXI running the cavity simulator (top), up/down-converter (center), signal generators (bottom) and GUI (right).

CONCLUSIONS

In this paper a cavity simulator has been presented. The purpose of this simulator is to replace actual cavities and perform hardware-in-the-loop LLRF algorithm's debugging. The presented simulator not only features the electrical response of a real cavity for the transmitted and reflected voltages but also includes five mechanical modes that can be driven by the Lorentz force or microphonics. The simulator is currently being used to debug a Kalman filter to estimate the detuning of an SRF cavity using an mTCA chassis.

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