DEVELOPMENT OF SCRF CAVITY RESONANCE CONTROL ALGORITHMS AT FERMILAB*

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Abstract

Lorentz Force Detuning (LFD) and microphonics compensation algorithms for pulsed SCRF cavities have been studied using CCII at Fermilab [1]. Feed-forward LFD compensation reduced detuning during the flattop from 165 Hz to 4 Hz. A slow feedback loop reduced detuning due to pressure variations from more than 100 Hz to less than 10 Hz. An optimized feed-forward piezo compensation waveform reduced detuning due to residual vibration by a factor of 2. In CW mode, a fast feedback loop suppressed detuning due to external vibrations by 15 dB.

INTRODUCTION

Capture Cavity II (CCII) is a Tesla type super conducting radio frequency (SCRF) cavity installed in the Meson Lab at Fermilab. The cavity can be operated at gradients of up to 27 MV/m. CCII is equipped with a stepper-motor driven slow tuner to adjust the resonance frequency of the cavity and a piezo fast tuner to compensate for the dynamic detuning caused by the Lorentz force at high gradients and for slow drifts in the cavity tune such as those caused by pressure variations [2].

LORENTZ FORCE DETUNING COMPENSATION

Piezo Control Systems

The 1.3 GHz RF signals from CCII were down-converted to an IF frequency of 13 MHz, and the IF signals were processed further using one or both of the following systems.

- An I/Q demodulator.
- A digital down-converter (DDC).

The demodulator is a prototype of a production system designed for use in the ILC Test Area in the New Muon Lab at Fermilab. The digital down-converter was used to cross-check the results obtained using the demodulator. To monitor vibration, both ends of the cavity were instrumented with Endevco Model 7703A accelerometers.

Analog Devices 8833 I/Q demodulators shifted the 13 MHz primary IF signals to baseband. The baseband signals were then digitized at a rate of 128 kHz using a 18-bit National Instruments NI PXI-6289 digitizer. The digitizer was read out using Labview and the forward I/Q and probe I/Q waveforms for each RF pulse were recorded to disk. Bench tests of the I/Q demodulator showed that it was capable of measuring the relative phase of the forward and probe IF waveforms to a precision of 0.2°.

The DDC directly digitized the 13 MHz IF signals using a 105 MS/s, 14-bit, Lyrtech VHS-ADC digitizer/FPGA board. In the FPGA, the digitized waveforms were shifted to baseband, filtered using a 100 kHz low-pass filter and decimated by a factor of 34. The decimated data was readout and recorded to disk using Labview. Bench tests showed the down converter was capable of measuring the relative phase of the IF signals to better than 0.05°.

LFD Compensation

The cavity equation can be used to determine the instantaneous detuning of the cavity [3,4]:

$$\frac{dV_{Cav}}{dt} = (\omega_{1/2} + i\delta)V_{Cav} + 2\omega_{1/2}V_{Fwd}.$$

In this equation, V_{Cav} is the complex envelope of the cavity voltage, $\omega_{1/2}$ is the cavity bandwidth, δ is the detuning of the cavity and V_{Fwd} is the complex envelope of the forward power signal. The cavity equation can be rearranged to give the instantaneous detuning:

$$\delta = \mathrm{Im}\left(\left(2\omega_{1/2}V_{Fwd} - \frac{dV_{Cav}}{dt}\right)/V_{Cav}\right).$$

Figure 1 shows the detuning of the cavity during the RF pulse at an accelerating gradient of 20 MV/m (open loop LLRF control) as the piezo bias voltage is varied between 0 and 100 VDC.

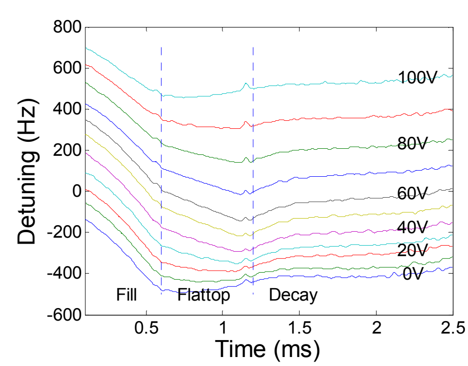

Figure 1: Instantaneous detuning of the cavity during the RF pulse as a function of piezo bias voltage.

The cavity slow tuner has been set so that the cavity is on resonance at a piezo bias voltage of 50 VDC. As the

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piezo bias is changed in either direction, the detuning during the pulse is reduced because the gradient falls as the cavity moves off resonance. At resonance, the tune of the cavity can shift by several hundred Hz during the 0.6 ms flattop.

In extracting the detuning, the relative normalizations of the probe, forward, and reflected waveforms were required to satisfy $V_{Probe} + V_{Forward} + V_{Reflected} = 0$, and smoothed using a Gaussian filter. The waveforms were also checked for cross-contamination of the forward and reflected signals.

LFD Compensation Waveforms

Two approaches for determining suitable LFD compensation waveforms were compared.

In the first, following work at DESY and elsewhere [2,4,5], a raised-half-sine pulse or a full sine cycle was applied to the piezo prior to each RF pulse. The frequency of the sine cycle was chosen to match the dominant mechanical resonance of the cavity, 180 Hz, in order to minimize the piezo drive voltage. The detuning of the cavity during the flattop was minimized by manually adjusting the amplitude of the piezo drive voltage, the interval between the piezo and RF pulses, and the pre-detuning.

In the second approach, the piezo was excited by a sequence of two hundred 2-ms wide raised half-cycle sine pulses. Each tenth pulse, the interval between the RF and piezo pulses was increased by 1ms beginning at -10ms. The cavity detuning was measured for each pulse. The linear combination of these basis pulses required to minimize the cavity detuning during the flattop was determined using a least squares fit.

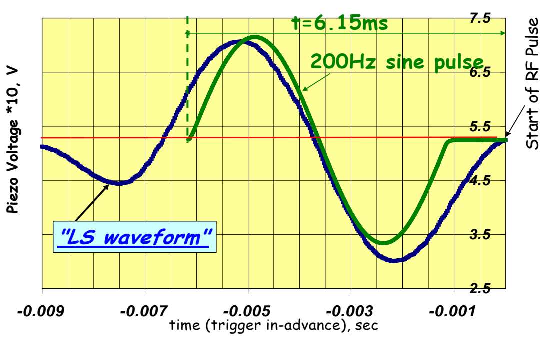

Figure 2: A comparison of LFD compensation pulses.

Figure 2 compares the manually optimized full-sine waveform to the least-squares waveform. The two pulses are similar in both magnitude and timing and reduce the Lorentz force detuning by comparable factors.

Figure 3 shows the phase of the CCII probe signal while the cavity is running at a gradient of 27 MV/m under open loop LLRF control. With the piezo pulse off (inset), the phase changes by more than 5 degrees over the flattop. With the piezo pulse on (main figure), the probe phase during flattop is flat to better than 1 degree. The detuning during the flattop, which depends on $d\phi / dt$, was reduced from 165 Hz to 5 Hz.

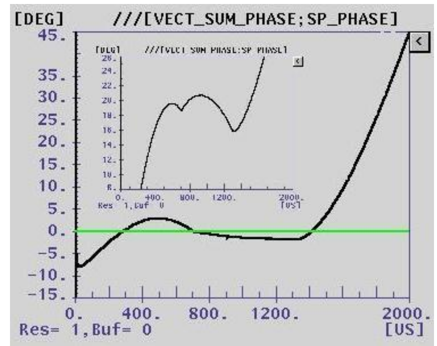

Figure 3: CCII probe phase with LFD compensation on and off.

Although both approaches described here reduce the LFD by comparable factors, each time cavity operating conditions were changed, considerable effort was required to identify a suitable set of parameters using the "standard" approach. In contrast, the least-squares approach was able to automatically find a piezo drive signal that worked as well or better than the "standard" waveform. In the future, a fully adaptive version, based on a recursive least squares fit will be studied.

MICROPHONICS

The cavity can be detuned during the RF pulse not only by the Lorentz force, but also by mechanical vibrations. It is convenient to classify vibrations according to their source.

- Liquid helium pressure fluctuations can induce very slow vibrations, (~0.1-0.01Hz).
- At higher repetition rates, residual vibrations from previous RF pulses can be important.
- External noise sources such as vacuum pumps can be a significant source of detuning.

Pressure Fluctuations

While liquid Helium pressure fluctuations are more important at higher temperatures, even at 1.8K, the resonance frequency of CCII could slowly drift by several tens of Hz over a period of several tens of minutes.
The resonance of the cavity was stabilized by:

- Averaging the detuning at the center of the flattop over several pulses; and
- Adjusting the piezo bias voltage in a proportional loop based on the averaged detuning.

Figure 4 shows the tune of the cavity over two three minute intervals. In the first interval, shown by the red line, the cavity resonance is not stabilized and drifts over a hundred Hz. In the second, as shown by the green line, the proportional loop limits the drift to less than 10 Hz.

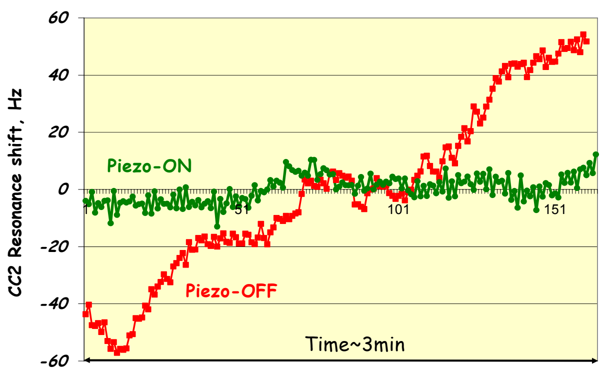

Figure 4: Resonance stability of CCII at 4K.

Residual Vibration

At a pulse repetition rate (PRR) of 5Hz, using either no LFD compensation or using the standard LFD compensation waveform, the pulse-to-pulse detuning increased to σ = 12Hz from σ = 5Hz at a PRR of 1Hz. The least-squares procedure described above was modified to find a compensation waveform that minimized a weighted sum of the detuning and the accelerometer vibration. Using this waveform at a PRR of 5Hz, the pulse-to-pulse detuning was reduced to σ=8Hz. Assuming the detuning due to residual vibration is uncorrelated with other sources, the vibration optimized waveform reduces the residual vibration detuning by a factor of 2.

External Sources

To further reduce the pulse-to-pulse detuning variation, the fast piezo tuner can actively damp vibrations induced

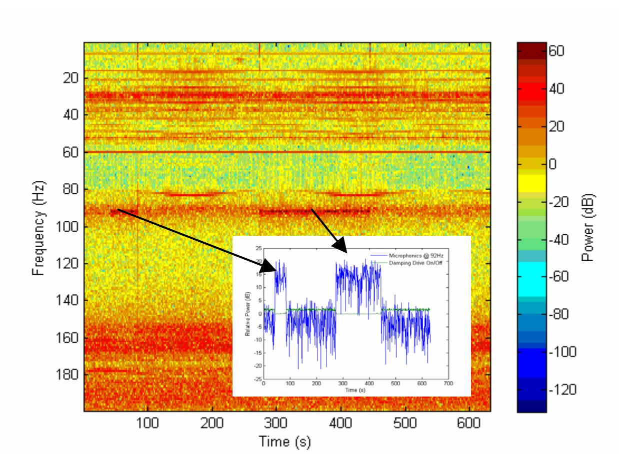

Figure 5: Active damping of externally induced vibrations.

by external sources. Figure 5 shows a spectrogram of the relative phase of the forward and probe signals while CCII was operated in CW mode. A number of strong spectral lines are visible. An IIR filter bank was used to isolate and reverse the phase of the 86 Hz spectral line. The phase reversed signal was then fed back to the piezo tuner. The inset shows the magnitude of the line as the feedback is turned on and off. Active damping reduces the vibration at this frequency by 15 dB. In the future, damping of external vibrations in a pulsed mode cavity will be studied using the phase reversed signal from a vibration sensor to drive the piezo.

SUMMARY

Lorentz force detuning and microphonics compensation algorithms have been studied using CCII at Fermilab. The instantaneous detuning of the cavity during the RF pulse was determined using the cavity equation. Piezo compensation waveforms were determined using both the standard approach and using least-squares. At an operating gradient of 27 MV/m, both approaches reduced the detuning during the flattop from 165 Hz to 5 Hz. A slow proportional feedback loop reduced slow drifts in the resonance frequency due to pressure fluctuations from more than 100 Hz to 10 Hz. Use of an optimized piezo compensation waveform reduced residual vibration detuning by a factor of 2. Detuning induced by external vibration sources was suppressed by 15 dB in CW mode using a fast feedback loop to drive the piezo tuner.

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