RECENT PROGRESS AT FERMILAB CONTROLLING LORENTZ FORCE DETUNING AND MICROPHONICS IN SUPERCONDUCTING CAVITIES*

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Abstract

SRF cavities are susceptible to detuning by mechanical deformations induced by the Lorentz force and microphonics. Providing the RF overhead required maintaining the accelerating gradient in detuned cavities can increase both the capital and operating costs of superconducting accelerators. Recent work at Fermilab has shown that active vibration control using a piezo actuator can reduce both Lorentz Force detuning and microphonics to the point where negligible RF overhead is required to maintain the accelerating gradient.

INTRODUCTION

SRF cavities are commonly manufactured from thin sheets of niobium to ensure adequate cooling. The thin cavity walls can be distorted by forces from the electromagnetic field inside the cavity (the Lorentz force), by variations in the pressure of the surrounding helium bath, or by mechanical vibrations driven by external sources such as pumps. Distortion of the cavity walls can detune the resonance frequency.

As the cavity detunes more RF power is required to maintain the accelerating gradient. Fast piezo actuators were first employed at DESY to compensate for Lorentz Force [1] detuning in pulsed cavities. Piezo actuators have also been used at BESSY to control pressure induced detuning of CW cavities [2].

The SRF program at FNAL has built two ILC style cryomodules [3] and is developing cavities for the proposed Project X CW proton linac [4]. Piezo actuators have been used successfully with both pulsed and CW cavities to limit detuning to a small fraction of the cavity bandwidths. Residual detuning at this level requires very little additional power to maintain the gradient.

ADAPTIVE COMPENSATION OF THE LORENTZ FORCE DETUNING

The LFD control system developed at FNAL for nine-cell 1.3 GHz elliptical cavities of Cryomodule 1 employs an adaptive feed-forward algorithm to tailor the piezo drive waveform to the mechanical response of each individual cavity [5]. Figure 1 shows the detuning of the cavities in CM1 during the flattop prior to compensation. Figure 2 shows the detuning following compensation. Before compensation, the cavities can detune by up to several hundreds of Hz. Following compensation, the detuning during the flattop is less than 10 Hz in all cavities. The bandwidth of the CM1 cavities is approximately 200 Hz. Controlling the detuning reduces the power needed to drive these cavities by a factor of 2 or more. One of the eight CM1 cavities was not powered because a short circuit in the stepper motor leads connecting prevented tuning to the RF frequency.

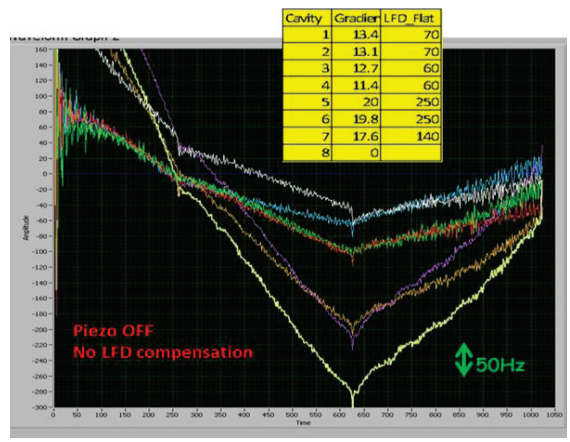

Figure 1: Uncompensated Lorentz Force Detuning in the CM1 cavities. The cavities can detune during the flattop by several hundreds of Hz.

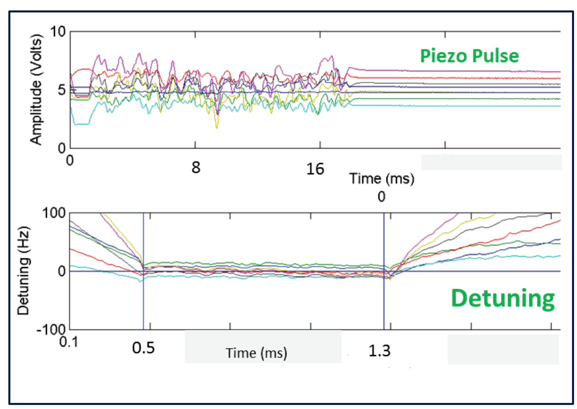

Figure 2: Compensated Lorentz Force Detuning for the CM1 cavities. The top plot shows the piezo drive waveforms while the bottom plot shows the detuning during the flattop. Active feed-forward compensation can limit Lorentz force detuning to 10 Hz or less.

Cavities can also be detuned by variations in the pressure of the helium bath. In addition to compensating for the rapid detuning induced by the Lorentz force, The CM1 LFD compensation algorithm monitors the cavity resonance frequency and adaptively adjusts the DC bias on the piezo actuator to stabilize the resonance frequency. Figure 3 shows how the resonance frequency of the CM1 cavities over a period of several hours when the adaptive compensation is not active. The resonance frequencies drift by up to 20 Hz.

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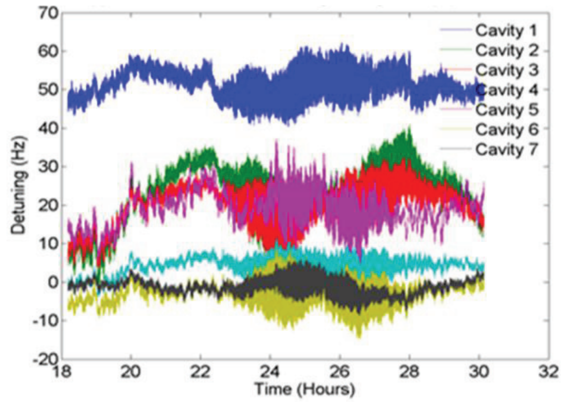

Figure 3: Frequency stability of the CM1 cavities over the course of 12 hours with non-adaptive LFD compensation. The cavity resonance frequencies can drift by several tens of Hz.

Figure 4 shows the resonant frequencies of the same cavities over a period of approximately 20 minutes when the adaptive feed-forward compensation is active. While the resonance frequency may still vary from pulse-to pulse by several Hz or more due to mechanical vibrations, when adaptive compensation is active, the long-term drift of the resonance frequency of every cavity is less than one Hz.

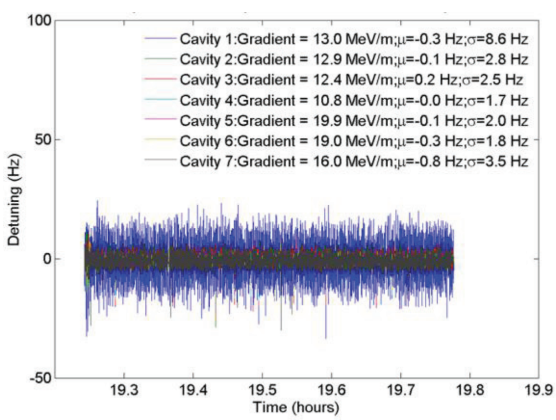

Figure 4: Fermilab CM1 tuning stability with adaptive feed-forward LFD compensation ON. CM1 operated at 5Hz repetition rate with closed loop LLRF. Adaptive feed forward can limit the drift to less than 1 Hz.

MICROPHONICS COMPENSATION

The control of detuning due to pressure variations and microphonics in CW and pulsed cavities is under continuing study at FNAL.

Previous FNAL publications have described

- The suppression of individual mechanical resonance lines of a CW 1.3 GHz, nine-cell elliptical cavity operating at 4K by up to 15 dB using an IIR filter-bank driven by the phase forward-probe phase difference [6];
- The use of a frequency-locked-loop to stabilize the resonance frequency of a narrow bandwidth (1.5 Hz) CW SSR1 325 MHz spoke resonator operating at 4K to within 1.3 Hz RMS/8Hz Peak as it was driven by a frequency-tracking RF control system [7].

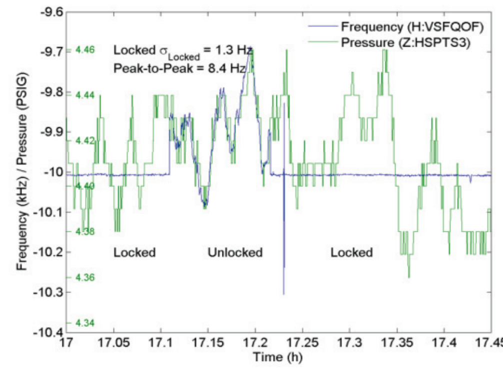

Figure 5: Active Compensation of Microphonics in the SSR1 Cavity. The green curve shows the pressure of the helium bath. The blue curve shows cavity detuning. The cavity was operating with a bandwidth of ~1.5Hz at the temperature 4.5K and E_{acc}=5MV/m.

Further tests using SSR1 cavity were conducted after a 102 Hz bandwidth coupler was installed in place of the original narrow bandwidth coupler. The cavity was again operated at a temperature of 4K while it was driven at a fixed frequency in open-loop by an Agilent RF generator though a solid state amplifier. The maximum attainable cavity gradient in this configuration was approximately 5 MV/m. The 13 MHz forward, reflected and probe IF signals from the RF control system were digitized using Lyrtech VHS signal processing board with 14 bit ADCs sampled at a rate of 104 MS/s and digitally down-converted in the onboard Virtex-IV SX-55 FPGA. The baseband forward and probe signals were mixed to give an I signal proportional to the magnitude of the probe signal and a Q signal proportional to the phase difference between the forward and probe. The phase difference was fed back to the piezo actuator through a combination of digital filters and integrators.

Figure 6 shows the detuning of the cavity over a period of approximately 25 minutes. The cavity is initially locked to the 325 MHz RF. Just after 17:08 (17.14 hours) the lock was dropped. As shown in the inset the cavity begins to track the He bath pressure. A few moments later FM modulation with a 50 Hz bandwidth was applied to the cavity drive frequency. The measured detuning tracks the modulation.

After the modulation was turned off, the cavity briefly returned to tracking the He pressure before the frequency lock was restored. With the exception of a single glitch at approximately 17:06 the cavity remained within 0.45 Hz RMS of the RF frequency during the time it was locked. The glitch is believed to be due to a problem in the firmware running on the FPGA at the time.

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Figure 7 shows a histogram of the detuning (blue dots) during the period the cavity resonance frequency was locked to the RF. The RMS detuning was 0.45 Hz. It is the peak detuning, not the RMS detuning however, that drives the cost of an accelerator using narrow bandwidth cavities. The peak detuning of SSR1 during this test was 1.46 Hz. When the resonance frequency was not actively stabilized, the pressure variations would drive the cavity completely off resonance within a few minutes or tens of minutes.

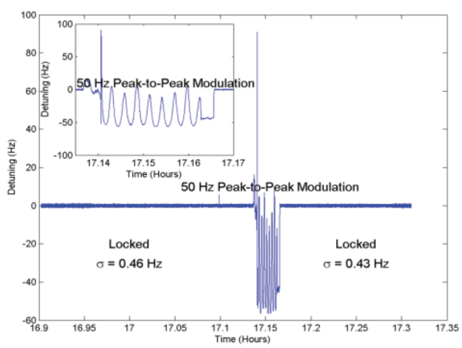

Figure 6: Microphonics detuning compensation of the SSR1 cavity. Cavity operating with half-bandwidth of 102Hz at the temperature 4.5K and E_{acc}=5MV/m. Insert: piezo compensation off; cavity frequency modulated by He pressure fluctuations and by FM of the driving frequency.

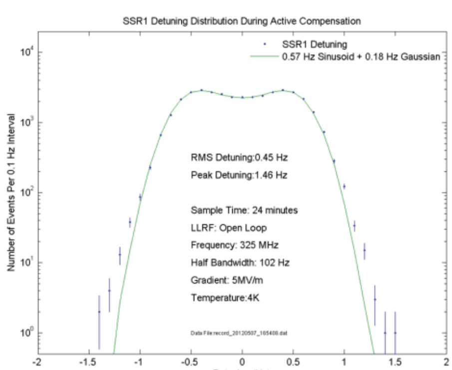

Figure 7: SSR1 cavity detuning (blue dots) distribution during the period (24min) the cavity resonance frequency locked to the RF. The green curve is a simulated distribution.

The detuning distribution is bimodal rather than Gaussian suggesting the detuning is limited by some systematic effect rather than noise. The green curve shows the histogram of a simulated signal consisting of a sine wave with additive Gaussian noise. The green curve reproduces the main features of detuning distribution well. This suggests the phase measurement may be contaminated by a sinusoidal frequency leaking into the baseband signal used to calculate the phase difference. Alternatively the detuning may be modulated by a cavity mechanical resonance. In the event that leakage is responsible for the bimodal distribution, the width of the detuning distribution could be narrowed significantly by suppressing that leakage, to perhaps to as little as 180mHz.

Figure 8 compares the SSR1 detuning distribution to the detuning distribution measured in HoBiCaT [2]. The SSR1 falls much more quickly and shows no evidence of the long tails observed there although the duration of the SSR1 measurements was not sufficiently long to draw any definitive conclusions.

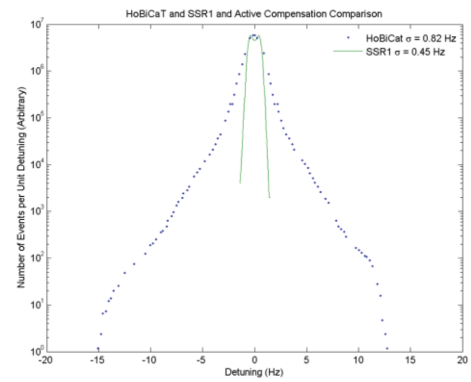

Figure 8: A comparison of the SSR1 cavity detuning (green curve) to the HoBiCaT results (blue dots).

CONCLUSION

Recent work at Fermilab has shown that active vibration control using a piezo actuator can reduce both Lorentz Force detuning and microphonics to the point where negligible RF overhead is required to maintain the accelerating gradient.

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