RESONANCE CONTROL FOR NARROW-BANDWIDTH, SUPERCONDUCTING RF APPLICATIONS*

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Abstract

Fast, active resonance stabilization has been attempted in several recent accelerator complexes, but has so far been unsuccessful. The next generation of superconducting accelerators will require both precise control of the gradient and active stabilization of the resonance frequency. Advanced techniques are being developed at Fermilab to monitor and correct for cavity detuning using fast piezo electric mechanical tuners. Results from recent cold cavity tests at Fermilab and Cornell University are presented.

INTRODUCTION

Many of the next generation of particle accelerators (ERLs, XFELs) are designed for relatively low, or even ideally zero beam loading. This leaves the ideal RF power requirement for the cavities dominated by wall losses and the power required to overcome detuning in operation. This smaller requirement means the cavities can operate with narrow bandwidths, minimizing capital and base operational costs of the RF plant. With such narrow bandwidths, however, cavity detuning from microphonics becomes a significant factor, and in some cases can drive the cost of the machine, see Figure 1.

Smaller bandwidths increase the fractional power increase for a given increase in detuning, and detuning environment is a very challenging thing to predict. Unlike beam loading, detuning spectrum can vary from cavity to cavity and hour to hour in an operational machine in a relatively unpredictable way. Additionally, mitigation/ improvement of the detuning spectrum is a very technical challenging task, requiring holistic approaches. Even if efforts at passive environmental detuning reduction are as successful as the best efforts of previous machines, active resonance stabilization will likely be required. Piezo actuators have been used with some success to actively stabilize cavity resonant frequencies in the past. This paper will present the results of ongoing detuning compensation efforts at FNAL using prototype 325 MHz SRF single spoke resonators (SSR) designed for the PIP-II project at Fermilab [1, 2] as well as 1.3 GHz 9-cell SRF cavities designed for the LCLS-II project at SLAC .

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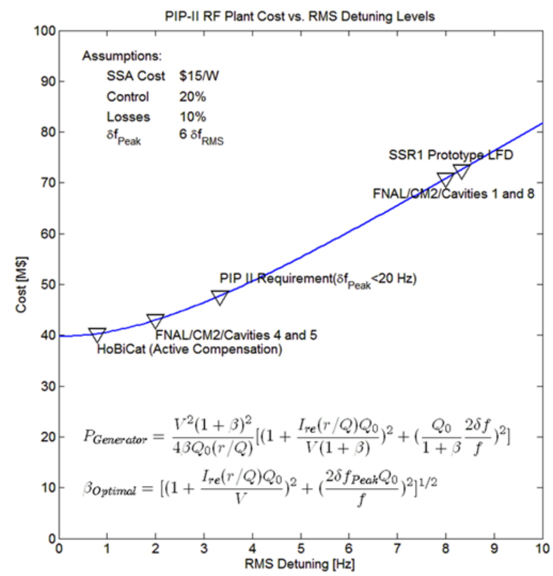

Figure 1: RF Generation Cost vs. Detuning Environment Example.

This work was done at the HTS and STC test stands at Fermilab as well as the HTC test stand at Cornell University.

PREVIOUS EFFORTS

Active compensation of both Lorentz Force Detuning and microphonics had been previously studied using an earlier SSR1 prototype with two different power couplers. An adaptive feedforward algorithm developed for pulsed 1.3 GHz 9-cell elliptical cavities [3] was able to reduce detuning in the spoke resonator from several kHz to 50 Hz or better during pulsed operation with a 150 Hz bandwidth power coupler [4].

SSR1 SPOKE RESONATOR

A dressed SSR1 cavity (SSR1-107) was installed in the Spoke Test Cryostat (STC) in May 2015. The cavity was equipped with a production coupler (60 Hz bandwidth), which was later reduced to 30 Hz with the addition of an air-side reflector in the drive circuit. The cavity was equipped with a production style tuner, including two piezoelectric actuators to provide dynamic tuning. This cavity had been the focus on an active design effort to reduce and minimize pressure sensitivity [2]. During these tests the cavity was powered by a 5 kW amplifier in both CW and pulsed mode, at both 4.5 K and 2 K.

LCLS-II 9-CELL RESONATOR

Three dressed 9-cell cavity tests (AES021/AES028/AES031) were tested for the LCLS-II project. Two (21 & 28) was tested at Fermilab using the Horizontal Test Stand, and one (31) was tested at Cornell University in their Horizontal Test Cryostat. All cavities were equipped with an LCLS-II compact tuner designed by Fermilab [5]. This tuner includes piezoelectric stacks in series with the slow tuning mechanism to provide fast tuning. All three were equipped with high-power production style couplers, giving the cavities half-bandwidths of 11 Hz, 27 Hz, and 11 Hz respectively. All tests were powered by a 10 kW amplifier CW-mode at 2 K.

FEED FORWARD COMPENSATION OF PONDEROMOTIVE EFFECTS

Radiation pressure from the EM fields in a powered resonator induces a mechanical deformation which in turn leads to shifts the cavity resonance frequency. The distortion this causes in the cavity frequency response can be seen in Figure 2.

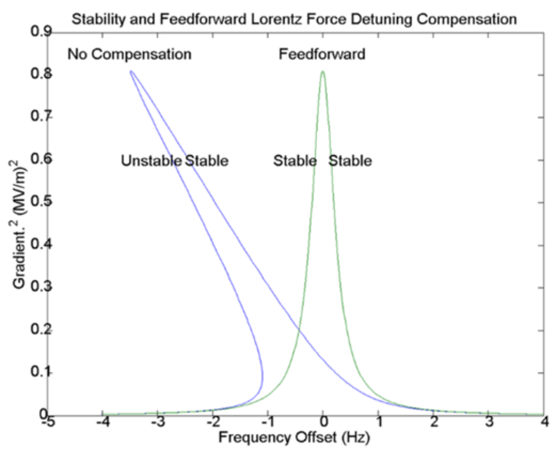

Figure 2: Cavity frequency response distortion without compensation (blue curve) and with compensation (green curve). Simulation for cavity with bandwidth=1Hz and K_{LFD}=-4.3 .

When uncompensated, the cavity resonance becomes non-single valued, making operation on resonance unstable (pondermotive instability) [6]. To counteract Lorentz force detuning a feedforward compensation signal with voltage proportional to the square of the cavity gradient was applied to the piezo. The incident, reflected and transmitted signals were down-converted from full cavity frequency (325 MHz for SSR1, 1.3 GHz for LCLS-II) to 13 MHz, digitized at 104 Ms/s with 14 bit precision, and processed in an FPGA to generate a piezo drive waveform using a 104 MS/s, 14-bit DAC connected to a high voltage amplifier. When feedforward compensation was active the cavity responded over a much narrower band as the drive frequency was swept as shown in Figure 3 and the cavity did not exhibit any sign of instability on the lower frequency side of the resonance when properly compensated.

Figure 3 shows the response of an LCLS-II cavity for different values of compensation. Starting from the left, with no compensation, the cavity falls off resonance once the edge of the resonance curve is reached. As the compensation is increased, the curve becomes more upright, passing through a symmetric resonance to become overcompensated, unstable in the other direction. The cavity behavior for LCLS-II cavities at both FNAL and Cornell was very similar.

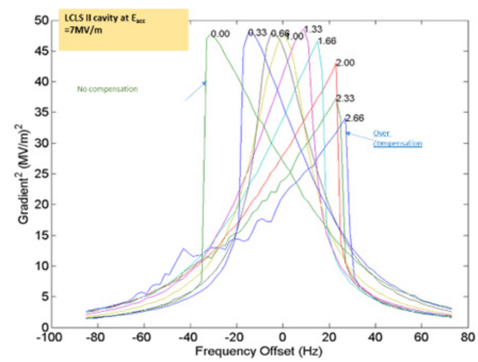

Figure 3: LCLS-II cavity frequency response for different LFD compensation coefficients.

This feed forward compensation method was very successful in stablizing the cavity resonance for all cavities it was applied to. This is not to say that there was no emergant behavior when it was applied. Figure 4 shows one of the more notable effects. As the compensation coefficient was increased, it appeared to drive certain sidebands. On the low frequency end of the spectrum, the highest compensation (blue curve) shows an additional bump. This is likely a side band positively reenforced, drawing the cavity closer to resonance as it passed through the resonance. As this is several bandwidths from the central resonance, no effects were expected or observed by this behavior.

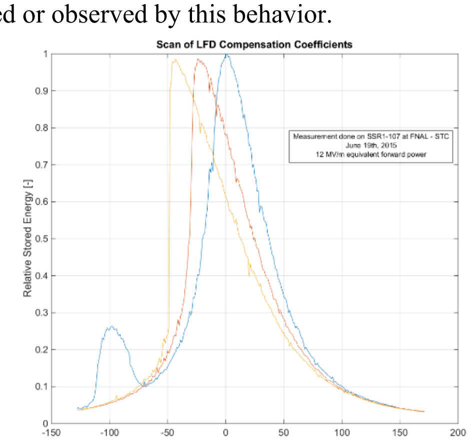

Figure 4: SSR1 resonance response for different LFD compensation coefficients.

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CAVITY CHARACTERIZATION

With the cavity pondermotive instabilities corrected, a phase lock was used in conjunction with the piezo tuner to characterize the cavity mechanical system. Piezo-Cavity transfer functions were measured by tracking cavity resonance while driving the piezo with a sinusoidal voltage at integer frequencies from 1-1000 Hz. Figure 5 shows an example of one of these measurements.

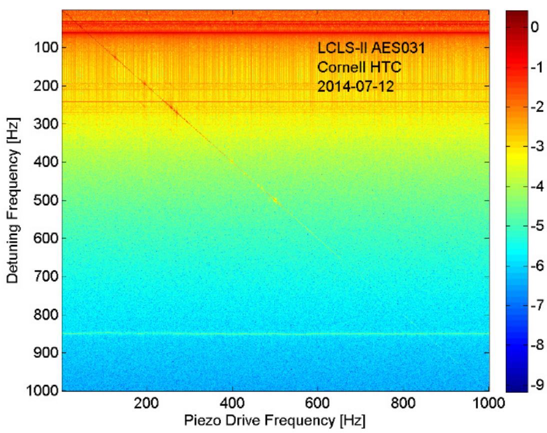

Figure 5: Spectrogram of an LCLS-II cavity transfer function taken at Cornell.

In Figure 5, we can see the direct drive and response of the piezo and cavity. As the piezo drive frequency crosses cavity mechanical resonances (~200, 270 Hz for this cavity), the detuning response intensifies. The magnitude and phase of the direct drive/response can be seen in Figures 6 and 7.

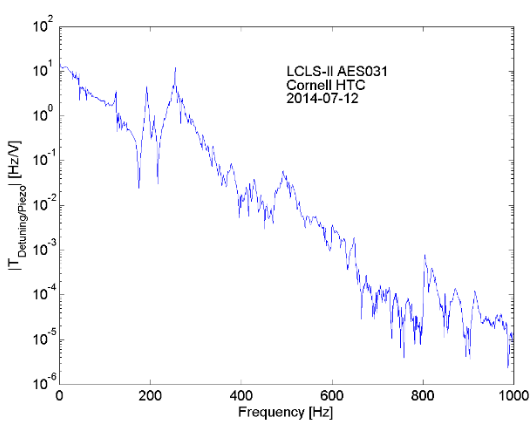

Figure 6: Transfer Function for AES031 taken at Cornell HTC.

As expected, these transfer functions agree between the three different LCLS-II cavities measured.

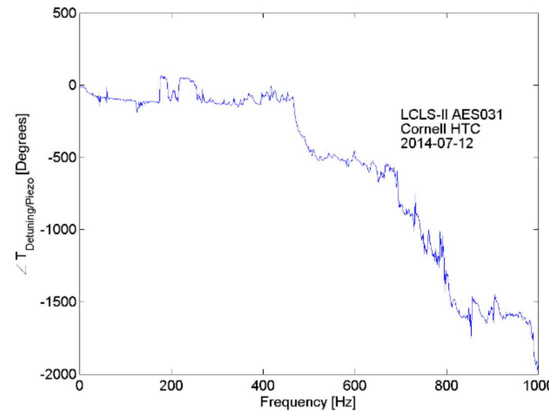

Figure 7: Transfer Function Angle for AES031 taken at Cornell HTC.

In addition to piezo transfer functions, amplitude transfer functions were measured. While the cavity resonance was tracked by phase lock loop, the drive amplitude was modulated by 5% at a modulation frequencies from 1 to 1000 Hz. The resulting transfer function can be seen in Figure 8. While the drive was modulated, LFD compensation was active.

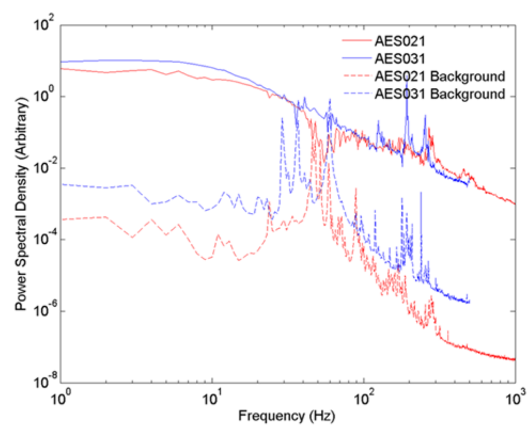

Figure 8: Amplitude Modulation transfer function measurement at FNAL and Cornell.

ACTIVE RESONANCE STABILIZATION USING FEEDBACK

Once ponderomotive effects had been suppressed using feedforward Lorentz force compensation, feedback proportional to the phase difference between the incident and transmitted signals was added to the piezo drive waveform generated by the FPGA. The combination of feedforward and fast feedback compensation successfully locked the cavity resonance to a fixed frequency open-loop RF drive signal but some long term drift was evident. The combination of feedforward, fast feedback and slow feedback was able to stabilize the SSR1 (325MHz) cavity resonance to within 11 Hz RMS of the drive frequency over a significant time period.

In Figure 9, the detuning stability at Cornell for AES031 is shown. Over a period of three hours, the resonance was stabilized to less than a peak detuning of 16.6 Hz, corresponding to an RMS detuning of 4.4 Hz. Later at FNAL, this work was extended during the test of AES021 and AES028, adding a narrow band resonance stabilization that was locked to the most prominent resonance line seen during these tests. The addition of this narrow band filter to the proportional feedback already used further improved the resonance stability for these tests, seen in Figures 10 and 11. Red line at 10Hz on the Figures 9, 10 and 11 is LCLS II technical requirements specification.

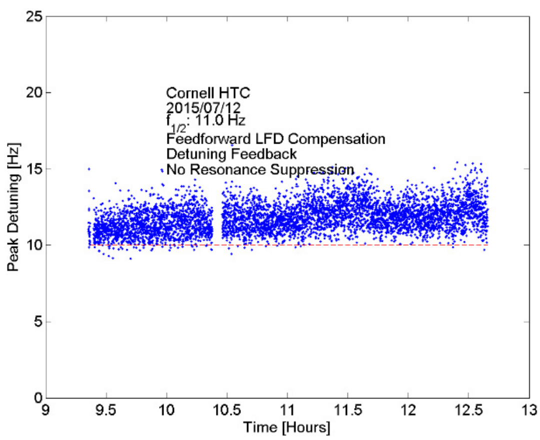

Figure 9: Cornell HTC resonance stabilization with proportional feedback.

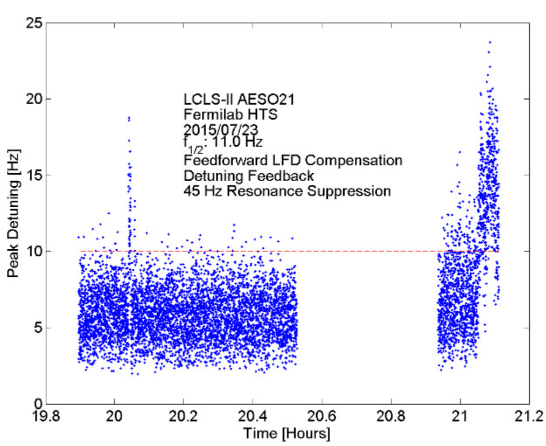

Figure 10: FNAL HTS test of AES021 with resonance stabilization with proportional feedback and narrowband resonance compensation of the 45 Hz mechanical driving term.

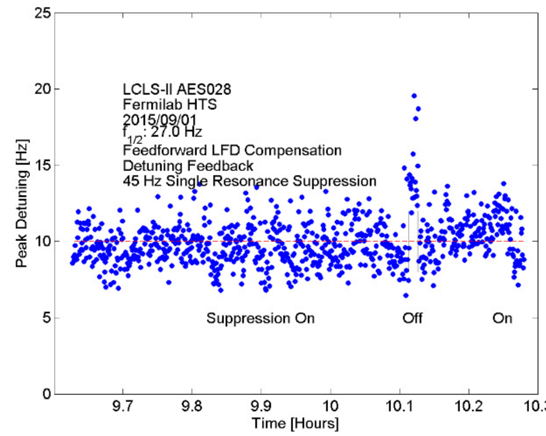

Figure 11: FNAL HTS test of AES028 with resonance stabilization with proportional feedback and narrowband resonance compensation of the 45 Hz mechanical driving term.

CONCLUSIONS

It has been clearly demonstrated that pondermotive instabilities can be directly compensated for two very different cavity geometries. Using the developed system, cavity characterization has been done to understand the coupled electromechanical system in an effort toward designing an optimal resonance controller. In addition to this, active stabilization of cavity resonances by proportional detuning feedback has been shown to be an effective strategy for reducing cavity detuning in a noisy vibrational environment. Supplemental feedback based on narrowband resonance feedback designed to suppress individual driving terms has allowed further reduction in detuning. This work will be extended to suppress multiple resonances simultaneously.

REFERENCES

[1] S. Nagaitsev, "Project X, new multi megawatt proton source at Fermilab", FROBN3, PAC2011, New York, USA.

[2] D. Passarelli, L.Ristori, "SSR1 Tuner Mechanism: Passive and Active Device" TUPP052, LINAC2014, Geneva, Switzerland.

[3] W. Schappert, Yu. Pischalnikov, M. Scorrano, "Resonance Control in SRF cavities at FNAL", THOCS5, PAC2011, New York, USA.

[4] Y. Pischalnikov, *et al.,* "Tests of a Tuner for a 325 MHz SRF Spoke Resonator", TUP080, PAC2011, New York, USA.

[5] Y. Pischalnikov, *et al.,* "Design and Test of Compact Tuner for Narrow Bandwidth SRF Cavities" WEPTY035, IPAC2015, Richmond, USA.

[6] J. R. Delayen, "Phase and Amplitude Stabilization of Superconducting Resonators", Ph.D. thesis, California Institute of Technology, 1978.

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