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ACTIVE MICROPHONICS COMPENSATION FOR LCLS-II*

J. P. Holzbauer†, B. Chase, J. Einstein-Curtis, Yu. Pischalnikov, W. Schappert
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
L. Doolittle, C. Serrano, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

Testing of early LCLS-II cryomodules showed microphonics-induced detuning levels well above specification. As part of a risk-mitigation effort, a collaboration was formed between SLAC, LBNL, and Fermilab to develop and implement active microphonics compensation into the LCLS-II LLRF system. Compensation was first demonstrated using a Fermilab FPGA-based development system compensating on single cavities, then with the LCLS-II LLRF system on single and multiple cavities simultaneously. The primary technique used for this effort is a bank of narrowband filter set using the piezo-to-detuning transfer function. Compensation automation, optimization, and stability studies were done. Details of the techniques used, firmware/software implementation, and results of these studies will be presented.

INTRODUCTION

The LCLS-II project includes a superconducting driver linac to accelerate 60 uA of electrons for X-ray generation. The SRF cavity technology used includes new hydrogen doping techniques that give a significant increase in the cavity quality factor. The relatively low beam current and low dynamic RF losses set the optimized cavity coupling factor relatively high (Q_L = 4.1e7) and design amplifier size relatively low (3.8 kW). These factors combined to give a peak detuning specification of 10 Hz [1].

Initial testing of the first production LCLS-II assembled at Fermilab (F1.3-01) measured much higher detuning than specification (~150 Hz vs. 10 Hz) [2]. As part of a significant effort put forward to diagnose and mitigate this detuning, a program was started to develop and implement fast, active resonance control using the LCLS-II LLRF system at the partner lab test stands (both Fermilab and JLab). Part of this plan was to leverage significant experience at Fermilab in this area [3, 4].

CRYOMODULE TEST FACILITY

At Fermilab, assembled LCLS-II cryomodules are tested in the Cryomodule Test Stand [2]. Each cryomodule is mounted and aligned between two fixed end caps which provide all cryogenics and vacuum connections and mimic the tilt of the LCLS-II tunnel at SLAC due to its 0.5% slope.

The test stand features a dedicated cryoplant to supply cavity and shield helium flows, LLRF/HPRF controls and amplifiers to drive each cavity individually, and instrumentation and controls for cryomodule testing, including all production sensors and additional diagnostics. All of these signals are logged in the Fermilab controls system, ACNET. Most notably, the LLRF control system includes the functionality to capture RF signals, including calculated detuning, for all eight cavities simultaneously and synchronously at 10 kHz for an arbitrary amount of time.

LLRF CONTROL SYSTEMS

The LCLS-II LLRF system was under development when the cryomodule tests started at CMTF [4]. An existing FNAL LLRF system was then installed to support the operations of the test stand, along with in-house electronics for resonance controls studies. As the LCLS-II LLRF equipment was built, it was installed and it can currently control 8 cavities simultaneously including the integration of the resonance controls hardware as it will be installed in LCLS-II. The co-existence of the two systems in parallel has allowed for a smooth transition from existing to new hardware without interrupting the test stand operations. It has also served as a platform for out-of-loop performance measurements of the LCLS-II LLRF system to validate the newly designed hardware.

LCLS-II CAVITY/TUNER DESIGN

The LCLS-II mechanical tuner [5] is a double level tuner with both course electromechanical actuator and fine (fast) piezoelectric tuner in series. These piezo tuners are installed such that they act directly on the cavity end flange, translating their stroke directly to the cavity flange. This was done intentionally to give better fast tuning resolution and lowest possible group delay.

Piezo-to-Detuning Transfer Functions

The bandwidth of direct PID feedback on detuning has been found to be limited by the mechanical resonance of the cavity/tuner packages. The standard technique done to measure these resonances is to characterize the piezo-to-detuning transfer function by driving the piezo with a fixed amplitude, fixed frequency signal and synchronously capturing piezo drive and cavity detuning. This measurement is repeated at a range of frequencies to characterize the mechanical system.

This technique was implemented in the LCLS-II LLRF system resonance control system. First, it was demonstrated on one cavity, but later expanded and optimized to characterize the full cryomodule simultaneously. For this, the signal chain (NCO -> DAC -> Piezo Amplifier -> Piezo -> RF signals -> Cavity Detuning) was needed for each cavity. The hardware already existed, so most of this effort

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†jeremiah@fnal.gov

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consisted of firmware and scripting development of the drive and capture systems. A procedure was developed to scan the same frequency range with all cavities with the drive frequencies staggered such that the different detuning contributions could be separated. All cavity drive and detuning signals were captured synchronously, allowing rapid measurement (1-2 hours depending on frequency range and resolution) of all transfer functions including cross talk between cavities. Figure 1 shows these measurements done recently on F1.3-09. After modification of the cavity 1 support structure [6], all cavity transfer functions are similar and agree well with previous measurements at Fermilab and elsewhere. The low frequency, small amplitude resonance is not well understood, but has been theorized to be either cavity transverse modes or coupler mechanical resonances.

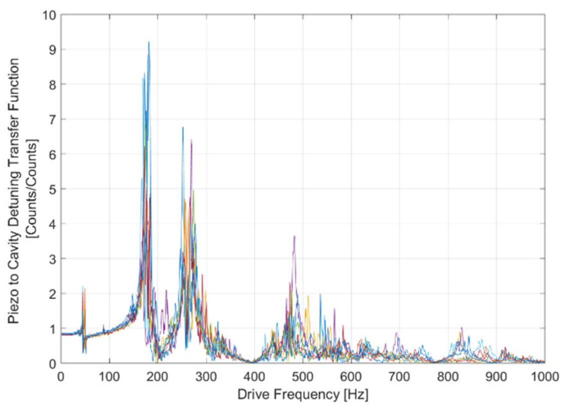

Figure 1: Eight cavity transfer functions measured simultaneously at CMTS-1 on F1.3-09.

Figure 2 shows the measured cross talk between cavities. This plot shows the cavity 1 piezo to all other cavity detuning transfer functions.

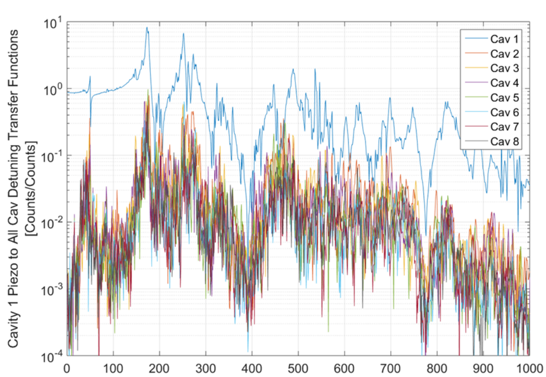

Figure 2: Cavity 1 piezo to all cavities detuning transfer function measured on F1.3-09.

In general, there is at least a decade of isolation between cavities, pushing two decades in the low frequency region. The lowest observed isolation is near mechanical resonances, suspected to be when cavity/tuner resonances line coincide. It is notable, however, that mechanical proximity in the string does not seem to play a significant role, indicating that transmission along cryomodule takes place in the mechanical strongback which would have a high transmission efficiency.

ACTIVE RESONANCE CONTROL

With the functionality of the LCLS-II LLRF system/resonance control system in place, the focus of the effort for ARC implementation was implementation of the compensation firmware (actual calculations, signal routing, capture functionality, etc.). This work went hand in hand with software and scripting for the same functionality.

Slow Resonance Stabilization

Slow resonance control (<1 Hz) was accomplished using an integrator with the cavity frequency detuning as the error. This loop is built-in to the resonance control firmware, allowing for unattended operation. Provision was also made to allow an external control system to have full access to the resonance control system functionality to run its own slow control loop. This functionality was used during GDR operation to both compensate for slow pressure fluctuations, but also to remove the manual tuning required to bring the cavity to resonance and the Lorentz Force Detuning when changing operational gradients.

Active Resonance Control Firmware/Scripting

The major firmware required for the compensation techniques used was a numerically control oscillator for diagnostics and characterization as well as a set of parallel, second-order IIR filters. Existing code was adapted for the LCLS-II architecture with the ability to implement either 16 or 32 filters per cavity. These filters can be driven by the NCO or (more typically) by the detuning signal. Scripting was developed to set these filter center frequencies, filter bandwidth, as well as output gain and phase rotation. The sum of these filter outputs is sent to the DACs, amplified and used to drive the piezo tuners.

Active Resonance Control Method

The goal of this effort was to provide a turn-key system for active compensation. This means characterizing the detuning spectrum and mechanical transfer function, automatically generating filter bank coefficients, and applying compensation. Manual tuning/adjustment must be kept to a minimum to make the system practical for a large operational machine.

Several compensation schemes have been tested, but the most successful was a scheme to deliver zero gain in the region of the cavity resonances. The cavity transfer function along with a detuning spectral background is used to automatically calculated filter coefficients.

Slow compensation is also required during fast compensation. The existing integrator-based scheme cannot currently be used in parallel with the filter-bank, and thus one of the filters is used as a slow-compensator, with the center frequency set to zero and the bandwidth set to 1/10 Hz.

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COMPENSATION TESTING RESULTS

Testing of the active compensation started with firmware and scripting validation. A single filter was optimized manually, adjusting gain and phase to specifically target a sizable detuning line on a single cavity. Once demonstrated, automatic compensation testing started.

Algorithm development first centered around characterizing the optimal overall gain and phase of the filters. This was done in scripting by scaling the gain of all filters excepting the zero-filter by the same factor, and was critical to diagnosing errors in automatic compensation scripting.

During the most recent cryomodule test (F1.3-09), the full transfer function characterization scheme was demonstrated, and individual cavity compensation was done on Cavity 8 (see Fig. 3). The detuning captured for the plots seen in this paper are capture by the AD-LLRF system, and are thus out-of-loop measurements of the cavity detuning.

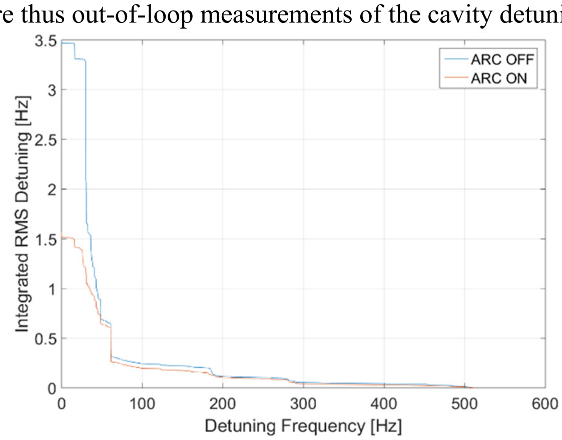

Figure 3: Integrated RMS detuning with and without ARC on only cavity 8 of F1.3-09.

As would be expected, most of the fractional improvement with ARC on is in the lowest frequency cavities. This is especially true for a significant 30 Hz detuning line seen on the cavity. With this one cavity running with ARC, the RF system was moved from SEL locking to GDR mode, first with the AD-LLRF RF system and later with the LCLS-II RF system. Short RF signal captures showed no loss of ARC performance.

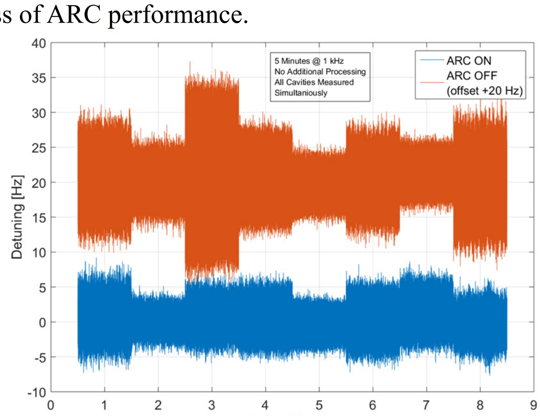

Figure 4: Short captures of all eight cavities with (blue) and without (orange + offset) ARC.

Once one cavity performance was demonstrated, the same technique was used to rapidly apply ARC to all eight cavities simultaneously (seen in Fig. 4).

With ARC applied, the cryomodule was held within the LCLS-II detuning specification, although testing time was not available for endurance studies. In all these measurements, as long as the overall gain factor was not above the instability limit, the compensation system was stable on all timescales observed.

In Fig. 5, the overall improvement with ARC on can be seen.

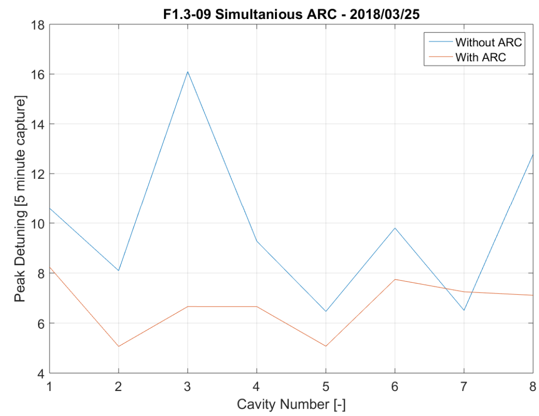

Figure 5: Peak detuning during 5 minute captures (at 1 kHz) by cavity with and without ARC.

CONCLUSION

Active resonance control of LCLS-II cavities has been demonstrated at Fermilab. While this has been shown on all eight cavities simultaneously and while operating in GDR mode, significant further optimization is possible, including endurance testing, detailed cross-talk studies, and further algorithm development.

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