INITIAL TEST OF A SRF CAVITY ACTIVE RESONATE CONTROLLER BASED ON MACHINE LEARNING METHOD*

Faya Wang†, Jorge Cruz, SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Abstract

We will introduce an active motion controller that leverages machine learning technology and electric piezo actuators. This controller will be specifically designed for active resonance control (ARC) of superconducting radio frequency (SRF) cavities. Our approach involves the initial development of a data-driven model to capture the dynamic behavior of the system, followed by the construction of a model predictive controller (MPC). The accuracy of the model has been validated through real cavity testing, and we are currently in the process of implementing the MPC on the existing hardware of the LCLS-II LLRF system. In our paper, we will present simulation results along with preliminary test results using actual SRF cavities from the LCLS-II SRF linac.

INTRODUCTION

Motion control plays an increasingly critical role in modern large accelerator facilities, such as 4th generation storage ring-based light sources, SRF accelerators, and high-performance photon beamlines. In the case of very high-Q SRF linacs like LCLS-II, precise cavity resonance control is essential to maintain stable operations. Failure to do so would necessitate a substantial increase in RF power, resulting in higher operational and capital costs due to the need for additional RF power sources.

The complexity of motion control in accelerator systems arises from the intricate interplay between the beam and electromagnetic fields with mechanical energy. For instance, in SRF cavities, electromagnetic modes are closely linked with their mechanical counterparts through Lorentz-force detuning and external microphonics. Due to the nonlinear nature of these couplings, resonance control, especially for SRF cavities, poses significant challenges.

Recent developments in ARC have shown promise in mitigating microphonics-induced detuning by manipulating piezo tuners. Notable examples of model-based controllers have been demonstrated at facilities like CBETA[1], Fermilab[2], DESY[3], and more recently at SLAC[4].

In this paper, we will introduce a data-driven ARC approach that leverages machine learning, specifically based on the Dynamic Model Decomposition (DMD) method. Our discussion will begin with modelling of cavity dynamics in the presence of microphonics by DMD, and will include the simulations of MPC performance. We'll then introduce the initial testing with real cavities. Finally, we will draw conclusions based on our study.

SIMULATION OF CAVITY RESONANCE CONTROL BY DMD

To construct an accurate data-driven model for SRF cavi-ty ARC, we employ an equivalent circuit model to simu-late cavity dynamics in the presence of microphonics, as depicted in Fig. 1. where it has $\omega_0 = \frac{1}{\sqrt{LC}}, \frac{R}{Q} = \sqrt{\frac{L}{C}}$, cavity half bandwidth $\omega_{1/2} = \frac{\omega_0}{2Q_L}$, and Q_L cavity loaded Q factor.

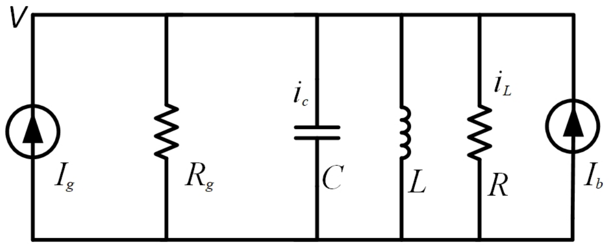

Figure 1: The equivalent circuit model of a cavity.

The transient behavior of the cavity can be described by the following equation:

$$\frac{d\boldsymbol{V}}{dt} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{bmatrix} \boldsymbol{V} + \begin{bmatrix} \omega_{1/2} & 0 \\ 0 & -\omega_{1/2} \end{bmatrix} \boldsymbol{V}_g, \quad (1)$$

where $\boldsymbol{V} = [V_r\ V_i]$ is cavity voltage envelop and $\boldsymbol{V}_g = [V_{gr}\ V_{gi}]$ is the generator voltage envelop.

The variation in the resonance frequency of the SRF cavity arises from deformations in the cavity body, initiated by fluctuations in helium pressure or the Lorentz force pressure due to the electromagnetic field within the cavity. The coupling between cavity deformation and detuning can be described using a single mechanical model [5], as follows:

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

where ω_m, Q_m and K_m are respectively the mechanical mode's natural frequency, quality factor and coupling factor. The total detuning of a cavity is the sum of the contributions of all mechanical models, denoted as $\Delta\omega = \Sigma\Delta\omega_m$.

---

* Work supported by the US Department of Energy, Laboratory Directed Research and Development Program at SLAC National Accelerator Laboratory, under Contract No. DE-AC02-76SF00515
† fywang@slac.stanford.edu

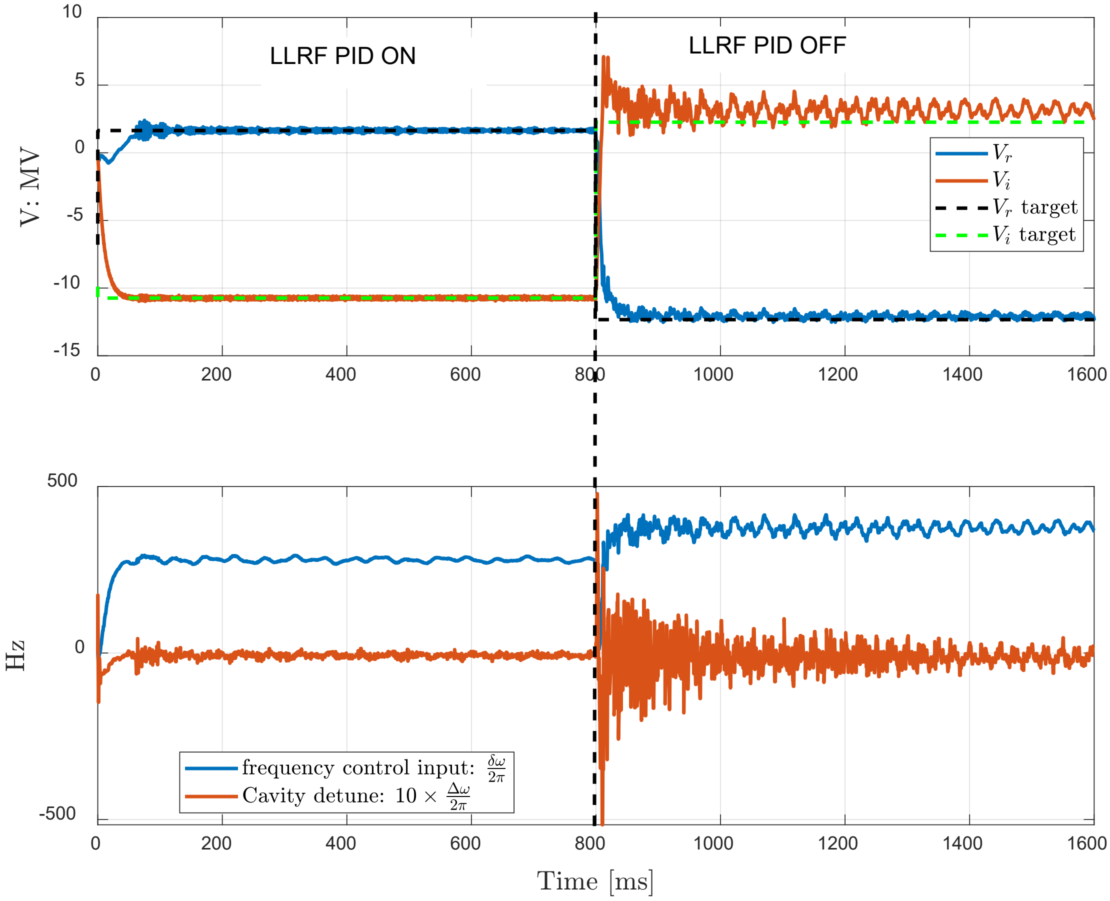

Figure 2: The simulation results of the MPC applied to the LCLS-II SRF cavity reveal a dynamic control process. Initially, the cavity is brought from a zero state to its target state solely through MPC control. As the cavity voltage approaches the desired target, the LLRF PID control is introduced at around 60 ms, providing fine-tuned control over the cavity field. Subsequently, at approximately 800 ms, the cavity is transitioned to a new target, and the LLRF PID control is deactivated. The MPC then takes over as the sole controller. Remarkably, the MPC effectively compensates for the substantial Lorentz detuning and ultimately stabilizes the cavity, maintaining detuning at around 1 Hz (rms).

Using the equations above, the dynamics of the cavity can be simulated. Subsequently, a data-driven model by DMD is employed to create a surrogate model. The forced cavity system can then be approximated as:

$$\boldsymbol{X}' = G \begin{bmatrix} X \\ U \end{bmatrix}, \tag{3}$$

where G is the operator matrix representing the forced system dynamics, $\boldsymbol{X}'$ and $\boldsymbol{X}$ respectively two system consecutive measurements at time step $k+1$ and k, and $\boldsymbol{U}$ control input at time step k.

As a result, a MPC is developed and its performance is evaluated, as illustrated in Fig. 2. The simulation involves the utilization of 32 mechanical modes with frequencies within 500 Hz on the LCLS-II SRF cavity, which has a half bandwidth of approximately 16 Hz.

Remarkably, the MPC demonstrates exceptional performance. It not only effectively maintains cavity detuning within 1 Hz (rms), but it also demonstrates the capability to navigate the cavity even in the presence of significant Lorentz detuning. For further in-depth insights into the MPC, readers are encouraged to refer to [6].

INITIAL TEST WITH CAVITY

In order to validate the effectiveness of the DMD method for modeling forced cavity resonance, real cavity tests were conducted. These tests were designed to maximize the extraction of hidden features by the model. To achieve this, the generator outputs were intentionally randomized to drive the SRF cavity, and a frequency chirp was employed to drive the piezo actuator.

The frequency of the piezo driver was maximized at 200 Hz, encompassing the possible range of microphonics, and its amplitude was set at approximately 20 times the cavity's half bandwidth. The sampling rate used for data acquisition was carefully chosen to be at least 10 times higher than the highest disturbance frequency, and in this case, it was set at 16 kHz.

The outcomes of the test are summarized in Fig 3, revealing a test error of approximately 2.5%.

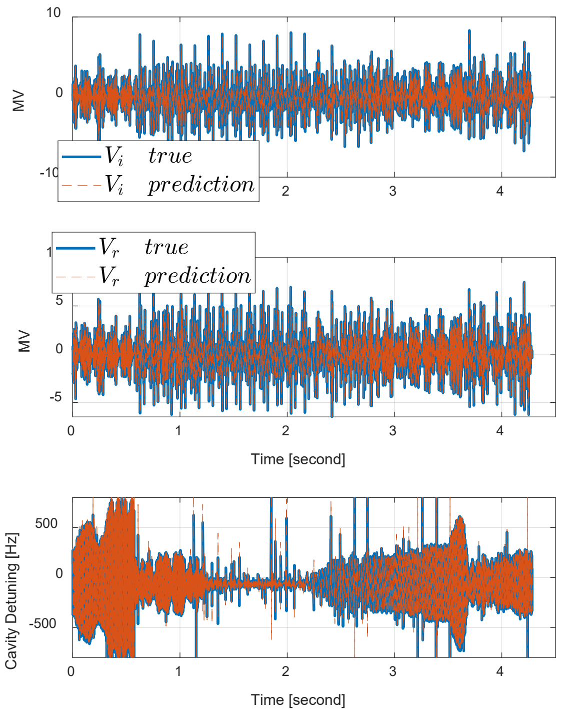

Figure 3: DMD test on LCLS II SRF cavity.

SUMMARY

We have successfully demonstrated a surrogate cavity resonance control model based on DMD through simulations and initial cavity testing. This model will serve as the foundation for the development of a MPC designed for SRF cavity resonance control.

In the coming phases, our plan involves the implementation of this MPC on the existing LLRF hardware of the LCLS-II machine. Subsequent testing with real cavities will provide valuable insights. If our efforts prove successful, this technology has the potential to significantly enhance the efficiency and stability of SRF linac operations.

REFERENCES

[1] N. Banerjee, *et al.*, “Active suppression of microphonics detuning in high Q_L cavities”, *Phys. Rev. Accel. Beams*, vol. 22, p. 052002, May 2019. `doi:10.1103/PhysRevAccelBeams.22.052002`

[2] J.P. Holzbauer, *et al.*, “Passive microphonics mitigation during LCLS-II Cryomodule testing at Fermilab”, in *Proc. 9th Int. Particle Accelerator. Conf. (IPAC’18)*, Vancouver, BC, Canada, May 2018. `doi: 10.18429/JACoW-IPAC2018-WEPML001`

[3] R. Rybaniec, *et al.*, “FPGA based RF and piezo controllers for SRF cavities in CW mode”, IEEE-NPSS Real Time Conference (RT), Padua, Italy, p. 1-2, June 2016. `doi: 10.1109/RTC.2016.7543112.`

[4] A. Bellandi *et al.*, “Narrow bandwidth active noise control for microphonics rejection in superconducting cavities at LCLS-II”, in *Proc. 31st Int. Linear Accel. Conf. (LINAC’22)*, Liverpool, UK, Feb. 2022. `doi:10.18429/JACoW-LINAC2022-THPOPA21`

[5] P. Echevarria, *et al.*, “Superconducting radio-frequency virtual cavity for control algorithms debugging”, *Rev. Sci. Instrum.*, vol. 89, p. 084706, Aug. 2018. `doi: 10.1063/1.5041079`

[6] F. Wang, “Enhancing SRF cavity stability and minimizing detuning with data-driven resonance control based on dynamic mode decomposition”, *AIP Advances*, vol. 13, p. 075104, July 2023. `doi: 10.1063/5.0154213`