# FPGA Based RF and Piezo Controllers for SRF Cavities in CW Mode

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***Abstract*—Modern digital low level radio frequency (LLRF) control systems used to stabilize the accelerating field in facilities such as Free Electron Laser in Hamburg (FLASH) or European X-Ray Free Electron Laser (E-XFEL) are based on the Field Programmable Gate Array (FPGA) technology. Presently these accelerator facilities are operated with pulsed RF. In future, these facilities should be operated with continuous wave (CW) which requires significant modifications on the real-time feedbacks realized within the FPGA. For example, higher loaded quality factor of the cavities when operated in a CW mode requires sophisticated resonance control methods. However, iterative learning techniques widely used for machines operated in pulsed mode are not applicable for CW. In addition, the mechanical characteristic of the cavities have now a much more important impact on the choice of the feedback scheme. To overcome the limitations of classical PI-controllers novel real-time adaptive feed forward algorithm is implemented in the FPGA. Also, the high power RF amplifier which is an inductive output tube (IOT) for continuous wave operation instead of a klystron for the pulsed mode has major impact on the design and implementation of the firmware for regulation. In this paper, we report on our successful approach to control multi-cavities with ultra-high precision (dA/A<0.01%, dphi<0.02 deg) using a single IOT source and individual resonance control through piezo actuators. Performance measurements of the proposed solution were conducted at Cryo Module Test Bench (CMTB) facility.**

## I. INTRODUCTION

PRESENTLY both FLASH and E-XFEL facilities are operated in the pulsed RF mode in which accelerating field in cavities is present for approx. 1.3 ms with 10 Hz repetition rate. Superconducting technology which was used to build these facilities allows in the future to operate them in the continuous wave (CW) RF mode in which the accelerating field is present in the cavities for the 100% of time. Such change in the duty factor, allows lowering the electron bunches frequency while still providing high number of the laser pulses to the users. This is especially important for experiments utilizing slower detectors so that the experiment time and cost can be reduced.

Loaded quality factor ($Q_L$) of the cavity input coupler has to be increased from $4.6 \cdot 10^6$ to approx. $1.5 \cdot 10^7$ so that the accelerating field over 10 MV/m can be maintained, while the power dissipated in the coupler is kept below maximum (which is 2.5 kW per cavity in the E-XFEL design). The new $Q_L$ factor setting correspond to the bandwidth change of the cavities from 283 Hz to only 87 Hz which makes the system highly sensitive to the detuning of the cavities.

## II. SYSTEM SETUP

CW tests are performed in the Cryo-Module Test Bench facility at DESY [1]. In this facility one E-XFEL type cryomodule consisting of 8 TESLA type superconducting cavities can be tested at the same time.

For the control purposes the so called vector sum (VS) approach is used in which signals from the individual cavities are combined together to form one complex signal [2].

1.3 GHz RF signals are down-converted to 54.17 MHz prior to sampling with 81.25 MHz. Then a non I/Q detection algorithm is applied so that the in-phase (I) and quadrature (Q) signals are available for control signal generation [3].

Control signal is than up-converted back to 1.3 GHz with the vector modulator [4] which then drives the IOT preamplifier.

Tuning of the cavities can be performed for each of the cavity separately. For the microphonics compensation fast piezo tuners are used [5].

## III. DETUNING COMPENSATION ALGORITHM

Detuning of the cavities is computed with the first order cavity model in the FPGA in real-time using the forward and reflected wave signals, and signal of the pick-up antenna [6]. In the identified transfer function of the piezo actuator and computed detuning (fig. 1) mechanical resonances in the frequency range 30-49 Hz can be seen. This is also the frequency range where the most of the microphonics power is distributed (fig. 3).

The highly resonant detuning transfer function prohibits use of the classical PI controller to compensate for the cavity detuning in the frequency range of microphonics [7]. However, integrator feedback can be successfully used for cancellation of the steady state error and slow drifts of the detuning caused for example by the helium pressure instability.

In the area of acoustic noise cancellation methods based on adaptive feed-forward algorithms are successfully used. Most of them require access to the reference signal which is correlated to the disturbances acting on the plant.

In specific case of repeatable disturbances, reference signal can be synthesized. This is especially valid for the narrow-band disturbances, where both disturbance and the reference

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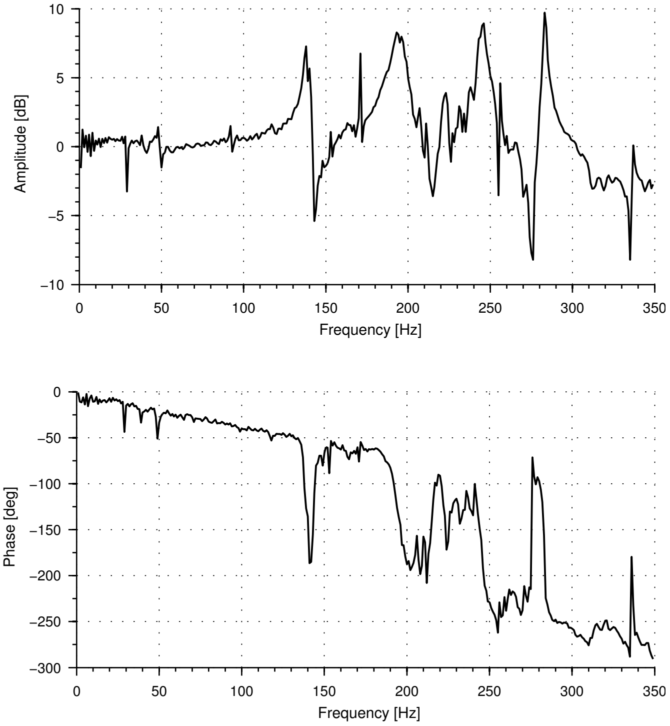

Fig. 1. Identified piezo actuator to computed detuning transfer function.

signal can be modeled as a sum of sine waves. Under such conditions feed-forward Active Noise Control (ANC) algorithm can be used [8].

Assuming that the plant is a linear system, the disturbance can be canceled by the sine wave signal of the same frequency as disturbance with the proper phase shift ($\phi$) and amplitude ($A$) applied to the actuator:

$$y = A\sin(\omega t + \phi).$$

It is more appropriate to represent the control signal in the in-phase and quadrature coefficients:

$$y = w_1 \sin(\omega t) + w_2 \cos(\omega t).$$

The $w_1$ and $w_2$ are linear parameters which can be adaptively modified using for example the Least Mean Squares (LMS) algorithm:

$$w_1(n+1) = w_1(n) + \mu e(n)\sin(\omega n - \Delta),$$

$$w_2(n+1) = w_2(n) + \mu e(n)\cos(\omega n - \Delta),$$

where $\mu$ is the learning rate of the algorithm which controls the convergence speed and the $\Delta$ is the delay introduced to compensate for the phase of the detuning transfer function.

## IV. EXPERIMENTAL RESULTS

During the tests both proportional RF feedback and detuning compensation feedback (including ANC, fig. 2) were operated simultaneously without loosing stability. Piezo integrator feedback was set to such as that unity gain was set to around 5 Hz. Two ANC frequencies were used: 49 and 30 Hz. Detuning of the cavities was controlled in order of 0.2 Hz RMS (fig. 3). Operation of the RF was possible up to approx. 12 MV/m and it was limited mainly by the maximum coupler power dissipation. Short term relative amplitude stabilization was 0.01% RMS and phase stabilization was $0.017^o$ RMS.

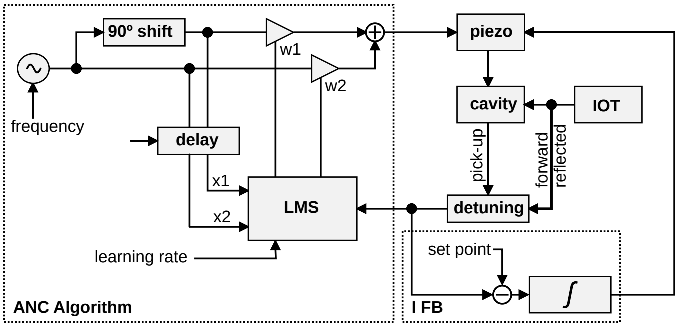

Fig. 2. Detuning compensation algorithm scheme.

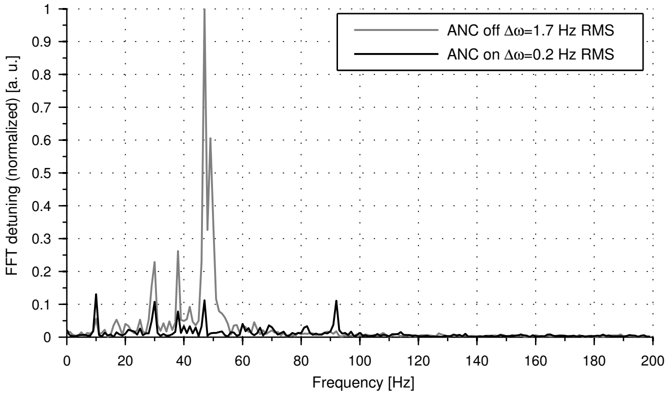

Fig. 3. Normalized detuning measurements for one of the cavity with ANC algorithm disabled and enabled.

## REFERENCES

[1] J. Sekutowicz, V. Ayvazyan, M. Barlak, J. Branlard, W. Cichalewski, W. Grabowski, D. Kostin, J. Lorkiewicz, W. Merz, R. Nietubyc, R. Onken, A. Piotrowski, K. Przygoda, E. Schneidmiller, and M. Yurkov, "Research and development towards duty factor upgrade of the European X-Ray Free Electron Laser linac," *Phys. Rev. ST Accel. Beams*, vol. 18, May 2015.

[2] T. Schilcher, "Vector sum control of pulsed accelerating fields in Lorentz force detuned superconducting cavities," Ph.D. dissertation, University of Hamburg, 1998.

[3] I. Rutkowski, R. Rybaniec, K. Czuba, Ł. Butkowski, M. Hoffmann, F. Ludwig, C. Schmidt, and H. Schlarb, "MTCA.4-Based Digital LLRF Control System for CW SRF Linacs," *IEEE Transactions on Nuclear Science*, 2015.

[4] I. Rutkowski, K. Czuba, D. Makowski, A. Mielczarek, H. Schlarb, and F. Ludwig, "Vector modulator card for mtca-based llrf control system for linear accelerators," *IEEE Transactions on Nuclear Science*, vol. 60, no. 5, pp. 3609–3614, Oct 2013.

[5] K. Przygoda, "Development of control system for fast frequency tuners of superconducting resonant cavities for flash and xfel experiments," Ph.D. dissertation, Politechnika Łódzka, 2011.

[6] R. Rybaniec, V. Ayvazyan, J. Branlard, Ł. Butkowski, S. Pfeiffer, H. Schlarb, C. Schmidt, W. Cichalewski, and K. Przygoda, "Real-time estimation of superconducting cavities parameters," *Preceedings of the 5th International Particle Accelerator Conference*, 2014.

[7] A. Neumann, "Compensating microphonics in SRF Cavities to ensure beam stability for future Free-Electron-Lasers," Ph.D. dissertation, Humboldt-Universität zu Berlin, 2008.

[8] S. Kuo and D. R. Morgan, "Active noise control: a tutorial review," *Proceedings of the IEEE*, vol. 87, no. 6, pp. 943–973, Jun 1999.