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MICROPHONIC DISTURBANCES PREDICTION AND COMPENSATION IN PULSED SUPERCONDUCTING ACCELERATORS

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Abstract

Accelerators are affected by the cavities detuning variation caused by external mechanical disturbances (microphonics). The paper presents microphonics estimation and prediction methods applicable for superconducting accelerators operating in pulsed mode. A mathematical model is built using the estimates of detuning during previous RF pulses. The model can be used for predictions of disturbances for the future time step and setup of the fast tuners accordingly. The proposed method was successfully verified with measurements conducted at the FLASH linac.

INTRODUCTION

Located at DESY, FLASH and currently constructed XFEL [1] are examples of the Linear Particle Accelerators (linacs) built using superconducting technology. Those linacs operate in pulsed mode regime. Because of the high operating gradients reaching up to 40 MV/m, during the pulse, RF cavities are detuned by the magnetic field pressure phenomena. In a RF cavity, electromagnetic field induces surface current and surface charges on the wall of the cavity. Interaction of the surface currents with a standing wave inside cavity generates a pressure, which mechanically deforms the cavity and as a consequence detunes it from the nominal frequency. In the literature it is known as Lorentz force detuning (LFD).

Another source of the detuning is caused by external mechanical forces acting on the RF cavities called microphonics. In opposite to the Lorentz force detuning, microphonics are generally not synchronized to the RF operation. Some sources of the microphonics are the helium plant, ground motions and man made machinery [2]. Pulsed mode operation at FLASH consists of the approx. 1.3 ms RF pulses with a repetition rate of 10 Hz. Time during the RF pulse is insufficient to measure the microphonic disturbance and compensate for it during the same pulse.

Due to a very high quality factor of superconducting cavities, detuning decreases the power transferred from the RF system. This reduces the RF system efficiency and also makes controlling stability of the accelerating gradient more difficult. In a situation where a high power amplifier is shared between many cavities, accelerating field control becomes more complicated, because detuning affects each cavity separately.

Conceptually (Fig. 1) it is possible to compensate for microphonics by predicting its level based on the information

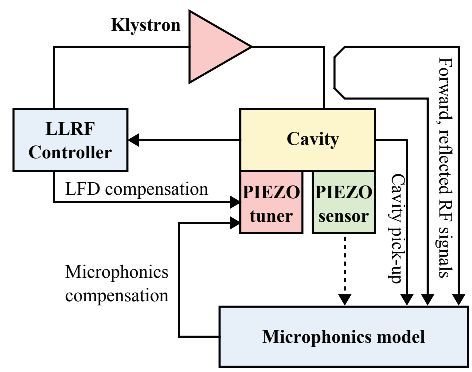

Figure 1: Block diagram of the proposed microphonics compensation method for a linac operating in pulsed mode.

from previous pulses. To enable this, a microphonics model has to be build during an operation of a facility. Possible information sources are RF signals during the pulse and (optionally) piezo sensors output in the time between the pulses. Piezo actuator can be used for fast tuning of the cavity based on the knowledge from the model, in the similar way as it is used for Lorentz force detuning compensation. This could decrease the amount of microphonic disturbances affecting the cavity.

In the paper a first implementation of this concept is evaluated. In the first attempt a simple auto-regressive (AR) model for the microphonics is used. Disturbances are estimated using the detuning computed from the RF signals. The method was validated with the open-loop measurements at the FLASH linac. First results show potential reduction of the detuning caused by microphonic disturbances in the accelerators operating in a pulsed mode.

MICROPHONIC DISTURBANCES ESTIMATION AND PREDICTION

During an operation of the facility, detuning of SRF cavities can be computed [3] using RF signals. This is accomplished with the first order cavity model [4]:

$$\frac{d\mathbf{V_c}}{dt} + (\omega_{1/2} - j\Delta\omega)\mathbf{V_c} = K_g \cdot \mathbf{V_g},$$

where $\mathbf{V_c}$ - cavity pick-up signal, $\omega_{1/2}$ - half-bandwidth of the cavity, $\Delta\omega$ - detuning and $K_g \cdot \mathbf{V_g}$ - is the calibrated generator voltage, calculated from the forward and reflected power signals. After separation of the real (I) and imaginary (Q) parts of the complex numbers, detuning can be

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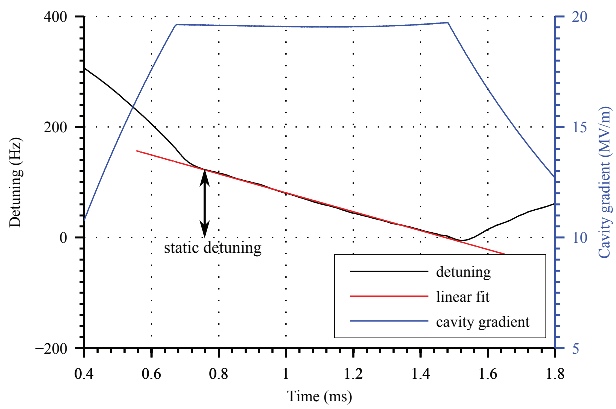

Figure 2: Estimated detuning curve with linear fit during flattop.

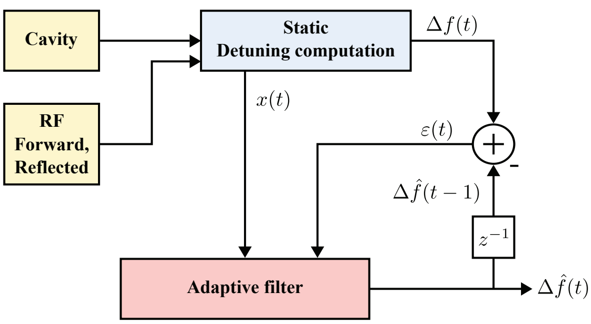

Figure 3: Schematic diagram of the microphonics prediction.

estimated using:

$$\Delta f = \frac{\Delta\omega}{2\pi} = \frac{1}{2\pi}\cdot\frac{I_c\cdot\left(\frac{dQ_c}{dt}-2\cdot K_g\cdot Q_g\right)}{I_c^2+Q_c^2} + \frac{1}{2\pi}\cdot\frac{Q_c\cdot\left(2\cdot K_g\cdot I_g-\frac{dI_c}{dt}\right)}{I_c^2+Q_c^2}$$

During a pulse flattop, a linear curve can be fitted to the detuning time plot (Fig. 2). Slope of this curve is related to the Lorentz force detuning (dynamic detuning) while its distance to the horizontal axis (for example measured in the beginning of the flattop) determines the static detuning. Changes in the static detuning from pulse to pulse can be interpreted as the microphonic noise.

Microphonic disturbances are modelled by a simple n parameters AR input-output model. Model's inputs vector x consists of a n static detuning estimates from a previous pulses:

$$x(t) = [\Delta f(t), \Delta f(t-1), \ldots\Delta f(t-n)]^T$$

Model's output y is a predicted static detuning during the next pulse (one step prediction), and can be computed as:

$$y(t) = \Delta\hat{f}(t) = \theta(t)x^T(t)$$

To identify the model parameters (θ) during the operation an adaptive normalized least mean squares filter [5] is used

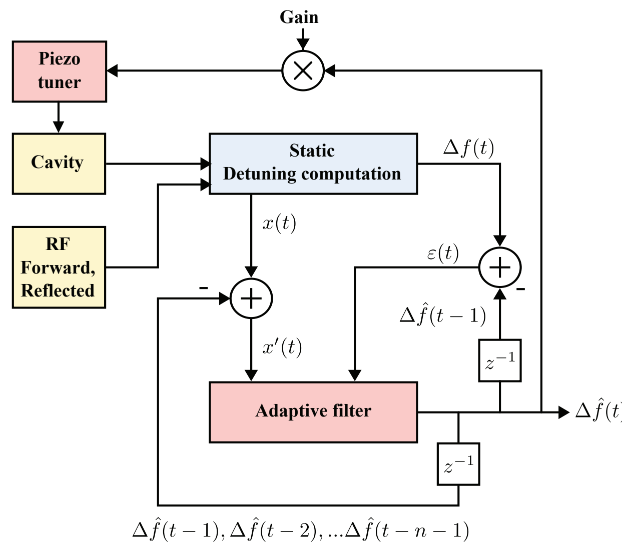

Figure 4: Schematic diagram of the microphonics compensation strategy.

(Fig. 3). Model parameters are changed in a recursive way that minimizes error ε between one step prediction of the static detuning and calculation after the RF pulse:

$$\varepsilon(t) = \Delta f(t) - \Delta\hat{f}(t-1)$$

The parameter vector is updated after each new RF pulse proportionally to the learning rate μ:

$$\theta(t) = \theta(t-1) + \frac{\mu\varepsilon(t)\Delta f(t)}{\Delta f^T(t)\Delta f(t)}$$

MICROPHONIC DISTURBANCES COMPENSATION

Predicted microphonic disturbances can be used for driving the fast piezo tuners. For the pulsed mode linacs dynamic mechanical model of the cavity-piezo system is not mandatory because we can assume that the tuners are driven advance in time so that steady state condition is reached before the RF pulse starts. In such circumstances piezo tuner model can be represented as a linear dependence between input control signal and detuning of the cavity. [6].

This leads to the feed-forward control scheme (Fig. 4), in which predicted detuning is applied to the piezo actuator with a constant gain. The gain has to be selected according to the piezo transfer function, and can be optimized during the operation of the algorithm. For the closed loop operation, disturbances prediction algorithm has to be modified in such way, that the control output signal is also included in the microphonics model. The most straight forward way is to subtract control signal from the input of the filter:

$$x'(t) = [\Delta f(t) - \Delta\hat{f}(t-1), \ldots\Delta f(t-n) - \Delta\hat{f}(t-n-1)]^T$$

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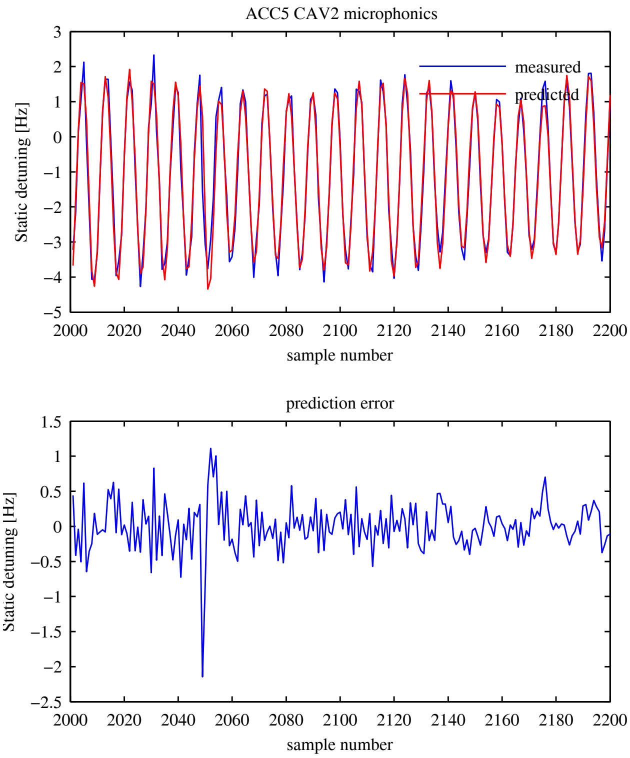

Figure 5: Static detuning and one-step prediction error at the FLASH ACC5 module cavity 2.

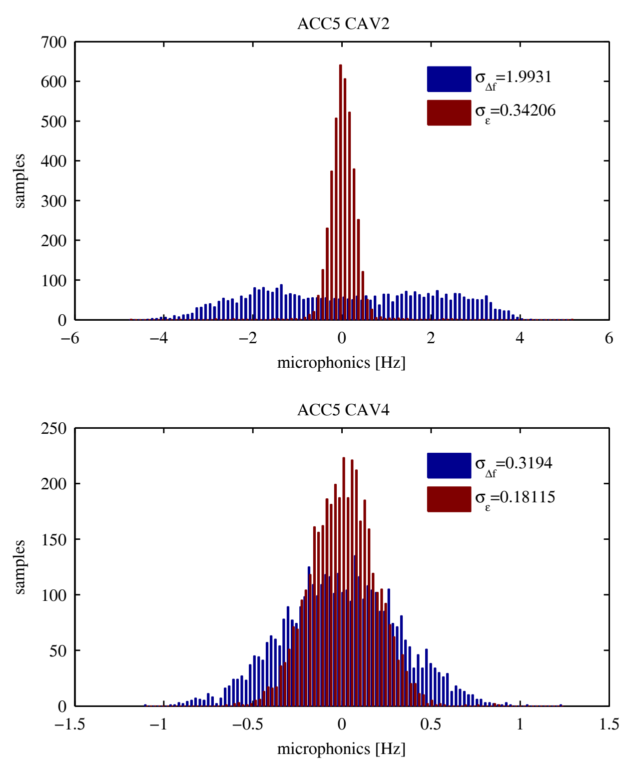

Figure 6: Histograms of the static detuning and one-step ahead prediction error of the proposed method for cavities 2 and 4 in the module ACC5 ($\sigma_{\Delta f}$ - standard deviation of the static detuning, σ_{ε} - standard deviation of the one-step prediction error).

MEASUREMENTS RESULTS AND OUTLOOK

Measurements were conducted at the FLASH linac. Microphonics were measured for all 8 cavities of the module ACC5. Overall 5000 RF pulses were taken for each cavity, which corresponds to 500 seconds of operation. Selected order of the model was 10, with $\mu = 0.125$.

Time plots of the prediction signals and related one-step prediction error of the proposed methods for cavity 2 are displayed in the Fig. 5. Each sample represents static detuning during single RF pulse. Histograms of the estimated static detuning and errors of the one-step ahead prediction (Fig. 6) shows that the cavity 2 is excited by the external disturbance of unknown source. For this cavity, compensation of the microphonic noise would be most beneficial. For other cavities across module ACC5 disturbance compensation is also possible, although expected outcome is less significant.

First results show that presented method can be used for potential compensation of the detuning caused by the microphonic disturbances at the linacs operating in a pulsed mode. Currently only the prediction part was verified using the measurements. However, performed numerical simulations, confirm that the proposed control strategy leads to the compensation of the microphonic noise affecting cavities.

In order to verify the performance of the proposed method, in the next step predicted microphonics should be used for controlling the fast piezo tuners. This includes development of the control software that would compute necessary information between the pulses. This method can be extended in such a way, that the information from the piezo sensors during the time between the RF pulses is also included in the model. Intensive verification of the complete solution has to be completed before this method could be implemented at the facilities.

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