ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF058

ANOMALY DETECTION FOR CAVITY SIGNALS - RESULTS FROM THE EUROPEAN XFEL

A. Nawaz*, S. Pfeiffer, DESY, Hamburg, Germany
G. Lichtenberg, Hochschule für Angewandte Wissenschaften, Hamburg, Germany
P. Rostalski, Universität zu Lübeck, Lübeck, Germany

Abstract

The data throughput of the European XFEL DAQ is about 1.5 Gb/s. Data depicting the cavity signal behavior is currently only saved manually. This either happens, when cavity tests are being performed, or an operator detects a fault in the cavity system, that has to be further investigated. Those instances of interest are neither systematically nor automatically stored. It can therefore be assumed that unwanted or degraded cavity behavior is detected late or not at all. It is proposed to change the focus from detecting known faults (such as quenches) to additionally detect anomalies in the cavity system behavior. In order to detect anomalies in the cavity signals, an algorithm is proposed using a cavity model. It aims on finding those data sets, which diverge from the nominal cavity behavior, saving those instances for later analysis. The nominal behavior is defined by the cavity electromagnetic resonance model with beam loading as well as the model for the mechanical oscillations due to the Lorentz Forces. By using such an approach, the detection of anomalies, as well as faults could be automated. This contribution aims to summarize the influence of beam loading on the detection and gives examples for anomalies that were found in several cavities.

INTRODUCTION

The European XFEL will soon have completed its first year in operation. Although the first user runs have been successful, it has become clear, that the large amount of components increase the need for automation. One aspect to obtain information about the reliability and quality of the beam, is the detection of faults and anomalies in the 808 superconducting cavities, operated in pulsed mode. In order to do so new algorithms have to be implemented, that can automatically distinguish between a nominal RF pulse and some abnormal behavior. This distinction can be performed by using a nominal cavity model, [1]. The model used takes into consideration the effect of Lorentz force detuning without beam loading. The sensitivity towards anomalies using a model based approach is dependent on the model uncertainty of the used model. This is why a close match between forward simulation and the real system output is important. The so-called nonlinear parity space method is used to define two *residuals*, that give information about how much the measured cavity signals have deviated from their behavior expected by the model, [2]. First results showed promising results for the detection of anomalous behavior just before a cavity quenched, [1]. This contribution aims to extend the proposed method for cavities with beam loading by using the bunch charge measurements of the toroids as an additional input in the model. Finally the properties of the residuals are evaluated for 450 individual cavities giving an example of detected anomalous behavior.

CAVITY MODEL

The electromagnetic field in a cavity is described by the voltage in a cavity $V_P = V_{P,I} + iV_{P,Q} = |V_P|e^{\phi_P} \in \mathbb{C}$ is dependent on the amount of the forward drive $V_F \in \mathbb{C}$ and the beam induced voltage $V_B \in \mathbb{C}$. Whereas the forward drive increases the field in the cavity, electron bunches accelerated on-crest reduce the field in the cavity. When the cavity is operated in closed-loop, beam loading compensation together with feedback and learning feedforward are compensating the reduction of the field, [3, 4]. The beam induced voltage is dependent on the charges of each bunch. These charges are measured with toroids and are typically in the range of 0.5 nC. In normal operation the electron bunches are accelerated on-crest and the bunch train starts at the beginning of the flattop of each RF pulse, see Figure 1. As the beam is used to define the phase of the cavity signals, the beam voltage mainly affects the in-phase component of the cavity field, i.e with a tuning angle of the cavity close to zero, [5]. The influence of the electron bunches on the RF field can therefore be described as first order differential equations by

$$\begin{aligned}\dot{V}_{P,I}(t) =& -\omega_{1/2}V_{P,I}(t) - \Delta\omega(t)V_{P,Q}(t) + 2\omega_{1/2}V_{F,I}(t)\\ & - V_B(t),\\ \dot{V}_{P,Q}(t) =& \Delta\omega(t)V_{P,I}(t) - \omega_{1/2}V_{P,Q}(t) + 2\omega_{1/2}V_{F,Q}(t)\,,\end{aligned}$$

where $\omega_{1/2}$ is the half bandwidth and $\Delta\omega(t)$ is the field dependent - Lorentz force - detuning, [5]. The beam induced voltage $V_B(t)$ can be described as an array of delta functions weighed with the charges of each individual bunch for the duration of the bunch train, i.e. maximum 650 μs at European XFEL, by

$$V_B(t) = \delta\left(t - kT_s^B\right)\hat{V}_B(kT_s^B),$$
$$\text{with } \hat{V}_B(kT_s^B) = \left(\frac{r}{Q}\right) q_B\left(kT_s^B\right)\pi f_0 \cos(\phi_P(k)),$$

where ϕ_P is the phase of the cavity voltage (for on-crest acceleration $\phi_P = 0$), T_s^B is the time between two consecutive bunches and $q_B(kT_s^B)$ are the bunch charges at time step k. The $\left(\frac{r}{Q}\right)$ parameter is about 1042 Ω for the superconducting cavities of the European XFEL operated with driving

* ayla.nawaz@desy.de

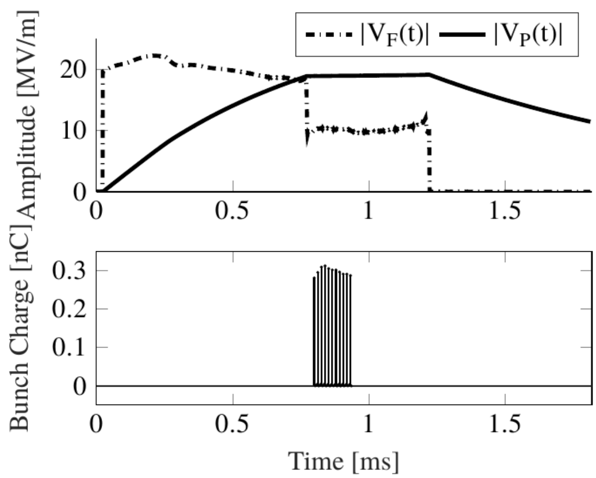

Figure 1: RF pulse with typical filling, flattop and decay in closed loop operation. The charges are measured by the toroid.

frequency of $f_0 = 1.3$ GHz. For the Lorentz force detuning $\Delta\omega(t)$ a first order approximation is used given by

$$\Delta\dot{\omega}_n(t) = -\frac{1}{\tau_n}\Delta\omega_n(t) + K_n\left(V_{P,I}^2(t) + V_{P,Q}^2(t)\right),$$

$$\Delta\omega(t) = \sum_{n=1}^{N}\Delta\omega_n(t),\ \forall\, n = 1,\ldots,N,$$

where N is the number of mechanical modes included to obtain a good fit between forward simulation and real measurements, [5]. Using the system identification toolbox of MATLAB, the Lorentz force coefficients K_n and the time constants τ_n were determined using the first of the set of pulses analyzed for each of the considered cavities. A total number of $N = 4$ modes were used to obtain a fit above 90%.

RESIDUAL GENERATION

In [1], two residuals were defined from the nonlinear cavity model. However, only the formulation of the first residual changes, when the beam is considered in the model. The following analysis will therefore concentrate on the first residual. Taking the beam induced voltage into consideration, the residuals are obtained by making use of redundant unmeasurable variables in the discrete time system representation of the model. The state space model can then be formulated as

$$x_1(k+1) = -a_0x_1(k) - q(k)x_2(k)T_s + b_0u_1(k) - u_3(k) \quad (1)$$

$$x_2(k+1) = q(k)x_1(k)T_s - a_0x_2(k) + b_0u_2(k), \quad (2)$$

$$x_n(k+1) = -a_nx_n(k) + b_n(x_1(k)^2 + x_2(k)^2),$$

$$y_1(k) = x_1(k) \quad \text{and} \quad y_2(k) = x_2(k),$$

where the detuning $\Delta\omega$ is approximated by

$$q(k) = \sum_{n=3}^{6} x_n(k) \quad (n = 3,\ldots,6),$$

and the remaining parameters by

$$a_0 = -1 + \omega_{1/2}T_s, \qquad b_0 = 2\omega_{1/2}T_s,$$

$$a_n = -1 + \frac{1}{\tau_n}T_s, \qquad b_n = K_nT_s.$$

The input $u_1(k), u_2(k)$ is given by the sampled forward drive signal of $V_{F,I}(t), V_{F,Q}(t)$ respectively, whereas the output $y_1(k), y_2(k)$ denotes the sampled measurable cavity field signals $V_{P,I}(t), V_{P,Q}(t)$. The additional input signal $u_3(k)$ is given by the beam induced voltage contribution $V_B(t)$.
The first residual is then obtained by making use of the redundant representation of $q(k)$ in (1) and (2). Solving both equations for $q(k)$ leads to

$$q^a(k) = \frac{-y_1(k+1) - a_0y_1(k) + b_0u_1(k) - u_3(k)}{y_2(k)}, \quad (3)$$

$$q^b(k) = \frac{y_2(k+1) + a_0y_2(k) - b_0u_2(k)}{y_1(k)}. \quad (4)$$

The residual is then defined by

$$r_1(k) = q^a(k)y_1(k) - q^b(k)y_2(k).$$

Using only the common nominator of (3) and (4) avoids numerical instability issues. This equation only holds as long as neither $y_1(k)$ no $y_2(k)$ are zero.
For the purpose of further analysis, three intervals of the residuals are evaluated for each pulse. The intervals

$$r^{filling}(p) = \bar{r}_1(k),\ 0 \le kT_s < t_1, \quad (5)$$

$$r^{flattop}(p) = \bar{r}_1(k),\ t_1 \le kT_s \le t_2, \quad (6)$$

$$r^{decay}(p) = \bar{r}_1(k),\ t_2 < kT_s, \quad (7)$$

correspond to the filling, flattop and decay of each RF-pulse p, with $\bar{r}_1^{filling}(p), \ldots, \bar{r}_1^{decay}(p)$ defining the mean over the defined intervals. The first residual is therefore the mean during the filling of the cavity ($kT_s < t_1$), the flattop ($t_1 \le kT_s \le t_2$,) and the decay ($t_2 < kT_s$).

Available Data The following data analysis makes use of cavity signals stored from the DAQ system during normal beam time operation. Due to some data storing issues, not all data of the 808 could be stored. In total the data of 450 cavities were available at the time and the analysis was conducted on 10 RF-pulses. The data from the DAQ is sampled with a $f_s = 1$ MHz frequency. The toroid signals on the other hand are stored with a sampling frequency of $f_s^B = 4.5$ MHz.

RESULTS

In Figure 2 the forward simulation using the input generated in closed loop for the model with and without consideration of the beam induced voltage is depicted. It is shown,

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF058

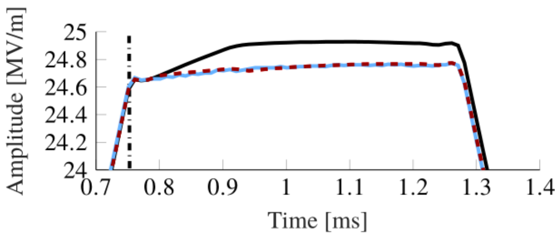

Figure 2: Cavity forward to probe simulation (1) and (2) with (dashed line) and without (normal black line) taking the bunch charges into consideration in the model compared to the measured probe amplitude depicted as light blue line.

that the simulation which includes information of the beam closely follows the real cavity output measurements, while the simulation without bunch charges shows significant deviations. A comparison of the residuals with and without beam loading, using the same RF pulses show the same the same qualitative behavior, whereas the residual with the beam is in general a factor of 10^{-8} smaller. Since the residual is a measure of consistency between input and output of the cavity system, the residual is only affected during the bunch acceleration. The effect of the beam compensation in the input, however is not significant. Due to a lower influence of model uncertainties during the decay, the variance in of $r^{decay}(p)$ is a factor of six smaller than the variance of the $r^{rise}(p)$ and $r^{flattop}(p)$. This means, that the residual of the decay is the most sensitive to changes.

Anomalies detected The filling and flattop show some similar, subtle differences, depending on the cavity number. Some anomalous behavior can be observed for three out of the ten pulses of the cavity with number 156, see Figure 3. The residual value shows a significant divergence from the nominal region. Figure 4 depicts the reason for this divergence. It is known, that a phase value of the cavity

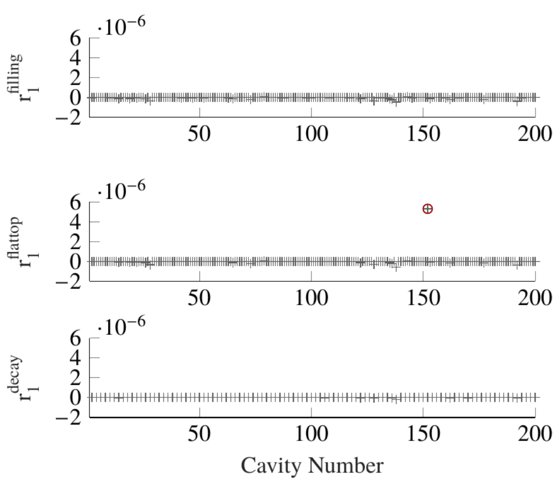

Figure 3: Residual of the filling, flattop and decay for 200 individual cavities during nominal operation. The anomalous residual is highlighted with a circle.

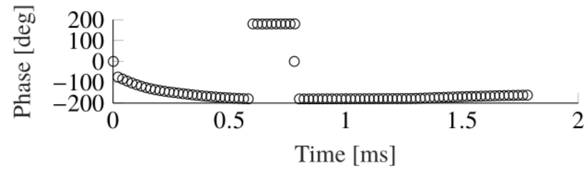

Figure 4: Anomly detected: phase flip during the flattop with intermediate value at zero.

near ±180° is ambiguous and can lead to sudden flips from −180° to +180° or the other way around. This is in general no problem, however in some cases the flip is performed with an intermediate value at zero which can not be real and seems to be an error in the phase computation. These events, although not immediately harmful should nevertheless be detected and monitored to improve the system reliability.

CONCLUSION AND OUTLOOK

It is shown, that the match of real data and forward simulation of the behavior of the superconducting cavities of the European XFEL is enhanced when taking into consideration the charges of the electron bunches. Using nominal measurements from 450 cavities, it is also shown, that this model enhancement has no influence on the detection of anomalies in the cavity signals. The entire analysis of the residual showed some anomalous behavior in five of the considered pulses in two cavities, that all showed a phase jump. These anomalies are currently not being detected, the proposed algorithm could therefore be used to obtain a more sophisticated method of obtaining performance and reliability analysis of the RF pulses and therefore the beam quality. As the results are encouraging, it is intended to implement this method in order to obtain a statistic about the amount of anomalous pulses as well as their effect on the beam performance.

REFERENCES

[1] A. Nawaz, S. Pfeiffer, G. Lichtenberg and P. Rostalski, "Anomaly Detection for the European XFEL using a Nonlinear Parity Space Method", Safeprocess 2018.

[2] J. Bokor, "Fault Detection and Isolation in Nonlinear Systems", 7th IFAC Symp. Fault Detect. Superv. Saf. Tech. Process., pp. 1–11, 2009.

[3] S. Pfeiffer, "Symmetric Grey Box Identification and Distributed Beam-Based Controller Design for Free-Electron Lasers", PhD Thesis 2014.

[4] C. Schmidt, "RF System Modeling and Controller Design for the European XFEL", PhD Thesis 2010.

[5] T. Schilcher, "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities", PhD Thesis, 1998.