ADAPTIVE SCHEME FOR THE CLIC ORBIT FEEDBACK

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Abstract

One of the major challenges of the CLIC main linac is the preservation of the ultra-low beam emittance. The dynamic effect of ground motion would lead to a rapid emittance increase. Orbit feedback systems (FB) have to be optimized to efficiently attenuate ground motion (disturbance), in spite of drifts of accelerator parameters (imperfect system knowledge).
This paper presents a new FB strategy for the main linac of CLIC. It addresses the above mentioned issues, with the help of an adaptive control scheme. The first part of this system is a system identification unit. It delivers an estimate of the time-varying system behavior. The second part is a control algorithm, which uses the most recent system estimate of the identification unit. It uses H2 control theory to deliver an optimal prediction of the ground motion. This approach takes into account the frequency and spacial properties of the ground motion, as well as their impact on the emittance growth.

INTRODUCTION

The attenuation of ground motion effects is one of the most challenging problems the CLIC (Compact Linear Collider) study is facing. By slightly displacing the accelerator components, ground motion causes emittance increase and beam jitter. Both effects result in a luminosity decrease, which has to be kept at a small value.
The problem of ground motion is well-known in the accelerator community. However, the ultra-low beam emittances make CLIC more sensitive to this parasitic effect than any other accelerator before. Therefore, it is essential to improve the performance of feedback systems, which are the main countermeasures against ground motion.
In this work we present an adaptive feedback algorithm, which focuses on the main linac of CLIC. It uses the BPM (beam position monitor) measurements to calculate new setpoints for the correctors distributed along the linac. Since the vertical beam emittance has tighter tolerances, we apply the algorithm just in this direction. The adaptive feedback algorithm consists of a system identification unit and a feedback controller (see Fig. 1). This scheme was chosen, because for the precise control we need in our application an accurate system model is indispensable. Drifts of certain accelerator parameters would lead to strong deviations of the initially measured accelerator model and the real accelerator, which degrades

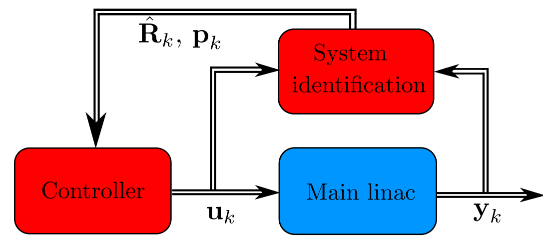

Figure 1: Adaptive feedback algorithm consisting out of a system identification unit and an on-line adaptable controller.

the controller performance. To address this problem we developed and implemented a system identification unit, which is capable of tracking changes of the accelerator behavior on-line. This has not only the advantage of better feedback performance, but also the down-time for the usual procedure of measuring the system behavior to establish an accelerator model can be saved.
The adaptable controller takes the model produced by the system identification unit and calculates from time to time new controller parameter. The design of the controller takes into account the time and spatial characteristics of the ground motion, by using its measured, two-dimensional PSD (power spectral density). It optimally minimizes the QP (quadrupole magnet) displacement, with the help of a LQG (linear quadratic Gaussian) controller. The controller progresses even one step further. It minimizes just that components of the BPM readings, which are harmfull to the beam. Long smooth spatial waves do not cause any significant beam quality increase and can remain uncorrected. By not reacting on this smooth ground motion, the controller can correct the harmfull components more efficiently.

USED MODELS

To develop the algorithms used for the adaptive controller, we have to introduce a state space model (see [2]) of the accelerator and the ground motion. The according block diagram is given in Fig. 2. In this plot k represents the time index of the time-discrete system, which has a sampling time of $20\,ms$. The dimension of all vectors is $N = 2010$, which corresponds to the number of QPs in the main linac and z stands (as usual) for the forward shift operator. The corrector values are symbolized by $\boldsymbol{u}_k$, which are displacements of all QPs produced by piezoelectric actuators. However, corrector magnets positioned at each QP could be used as well. In addition to the piezo-produced

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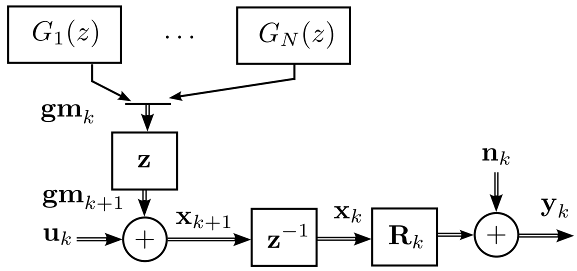

Figure 2: Block diagram of the accelerator and the ground motion models. Single lines indicate scalar values and double lines vectors.

displacement $\boldsymbol{u}_k$ the QP vertical position $\boldsymbol{x}_k$ is determined by the ground motion vector $\boldsymbol{gm}_k$. In the current model we use independent systems $G_1(z)$ to $G_N(z)$ to model the ground motion process. The assumption of independence is a simplification of the reality. The existing correlation was neglected to simplify the controller design. In order to be able to write the ground motion model in state space formulation, we use $\boldsymbol{gm}_{k+1}$. At the arrival of the next beam, the positions of the quadrupoles $\boldsymbol{x}_k$ are transformed by the orbit response matrix to the BPM (beam position monitor) readings $\boldsymbol{y}_k$. $\boldsymbol{n}_k$ is white Gaussian measurement noise.

SYSTEM IDENTIFICATION UNIT

To get a complete model of the system depicted in Fig. 2, the orbit response matrix $\boldsymbol{R}$ and the coefficients of the transfer functions $G_1(z)$ to $G_N(s)$ are needed. Since these parameters can drift, we focus on an on-line solution.

The on-line identification of $\boldsymbol{R}$ is a relative complex procedure, which is described in much more detail in [3] and [4]. It is based on the general principle of system identification, where a known input is applied to the system and the according output is measured. By using the input as well as the output data, system identification algorithms can establish an estimate of the real system. For the estimation of $\boldsymbol{R}$, we use the RLS (recursive least square) algorithm with exponential forgetting factor (see [5]). However, the standard algorithm cannot be applied in our case. The reason is that the usual excitation, resulting in beam oscillations, would lead to an unacceptable emittance increase. Instead a modified algorithm is used, which excites the beam just over a short distance, with the help of beam orbit bumps. Out of this local information an estimate for $\boldsymbol{R}$ is created. Since the details of this method are about to be published ([3] and [4]), they are omitted here. When creating a model of the ground motion, we assume (for sake of simplicity) that $G_1(z) = \cdots = G_N(z) = G(z)$. This corresponds to the assumption that the properties of the ground motion is not changing along the linac. The task is now to find a transfer function in z, which output signal has the same PSD as the ground motion signal, when the input of this transfer function is white, Gaussian noise with a certain variance. To do this we use the fact that the $PSD(z) = |G(z)|^2$. Tests have shown that the following model for $G(z)$ is rich enough to model the ground motion behavior accurately.

$$G(z) = k\frac{z^6 + \alpha_5 z^5 + \cdots + \alpha_1 z + \alpha_0}{z^8 + \beta_7 z^7 + \cdots + \beta_1 z + \beta_0} \qquad (1)$$

To find proper coefficients k, α_i and β_j (collected in $\boldsymbol{p}$), the nonlinear cost function

$$J(\boldsymbol{p}) = \int_{f_1}^{f_2} \left(0.5\log(PSD(f)) - \log(|G(f,\boldsymbol{p})|)\right)^2 df \qquad (2)$$

was minimized with the help of the Matlab function fmincon. $J(\boldsymbol{p})$ corresponds to the squared difference of the square root of the ground motion PSD and the magnitude of the ground motion model in an logarithmic scale. $G(z)$ is kept stable and minimum-phase, by adding some constraints on the nonlinear optimization problem. If the $G(z)$ is written in a factorized form, this constraints are actually linear.

FEEDBACK CONTROL

The choice of the control strategy is based on two facts, imposed by the beam physics of CLIC. The first is that the emittance and jitter increase is proportional to the square of the ground motion induced QP displacement. The cost function to minimize is therefore the L_2 norm of the QP displacements. In control theory this problem is well-known under the name H_2 optimization (see [2]). The solution for a subclass of this H_2 problems, is the LQG controller (linear quadratic Gaussian), which also applies to our problem. Since we assume that our actuators are very fast compared to the sampling time of the main linac, we can neglect them and the LQG controller reduces further to the negative output of a Kalman-filter.

The second important observation, gathered from simulations, is that not every QP missalignment causes emittance growth. Smooth disturbances (long wavelength) do not result in significant emittance growth. By neglecting this unimportant contributions, the Kalman-filter can put more emphasis on the important components of the ground motion and correct them more efficiently.

The former two observations lead to the new control algorithm depict in Fig. 3. The first step is to multiply $\boldsymbol{y}_k$ with

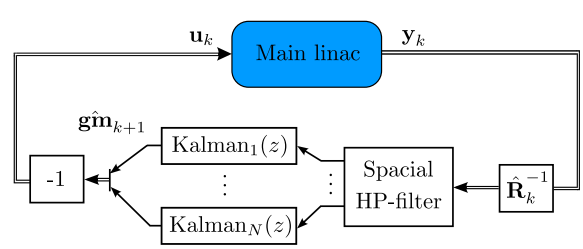

Figure 3: Block diagram of the ground motion optimized orbit feedback algorithm.

the inverse of the estimated responce matrix $\hat{\boldsymbol{R}}_k^{-1}$ to decouple the inputs and the outputs. Due to this operation N independent, small controllers (one per QP) can be designed instead of a single big one. The next step is to apply a spacial high pass filter to get rid of the unimportant ground motion components. An additional advantage of this filter is the reduction of the strong measurement noise amplification, due to the multiplication of $\boldsymbol{u}_k$ with the huge matrix $\hat{\boldsymbol{R}}_k^{-1}$. Finally the generated data are used by N independent Kalman-filters to generate optimal predictions for the significant ground motion components.

RESULTS

So far the individual parts of the adaptive controller have just been tested separately by PLACET simulations [1]. Figure 4 shows the identification result of the system identification unit for $\boldsymbol{R}$, due to a step-like change of the RF gradients within the allowed tolerances. While the initially measured matrix $\boldsymbol{R}_{k,m0}$ deviates strongly from the real matrix $\boldsymbol{R}_k$, the on-line estimated $\hat{\boldsymbol{R}}_k$ can recover from the initially large error. In Figure 5 the results if the nonlinear

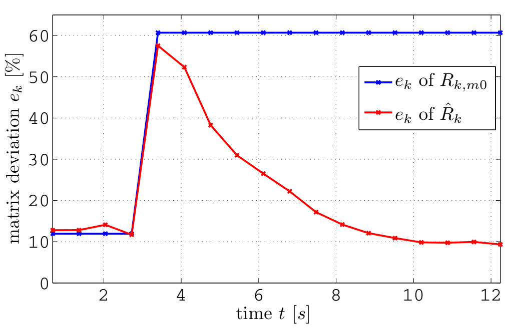

Figure 4: Absolute value error of the measured orbit response matrix $\boldsymbol{R}_{k,m0}$ and the on-line identified matrix $\hat{\boldsymbol{R}}_k$ compared to the real matrix $\boldsymbol{R}_k$. The plot is taken from [3].

optimization algorithm, that creates a model of the ground motion, is shown. The estimate fits very well to the filtered ground motion PSD. Recognize that for the Kalman-filter design the filtered PSD spectrum has to be used, due to the applied spacial high-pass filter in the controller. The results of the ground-motion optimized feedback controller are presented in Fig. 6. The emittance increase can be kept at an average level of about $0.3\,nm\,rad$. We assume that there is hardly any additional systematic emittance increase over time.

CONCLUSIONS AND FUTURE WORK

This paper presents the current stage of the ongoing work on an adaptive controller for the main linac of CLIC. The adaptive controller consists of the two subsystems system identification and feedback control.
The system identification unit establishes models for the orbit response matrix $\boldsymbol{R}$ and the ground motion process $G(z)$. The modified RLS identification algorithm works on-line

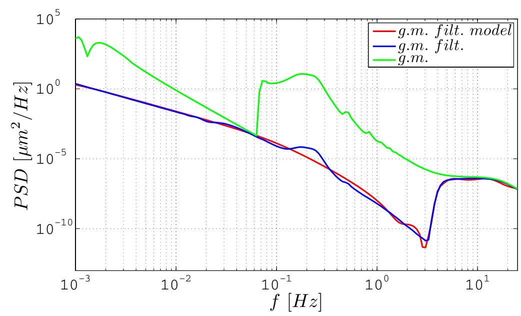

Figure 5: Comparison of the PSDs of the ground motion model B (see [6]) (green), the spacial filtered ground motion (blue) and the according model (red).

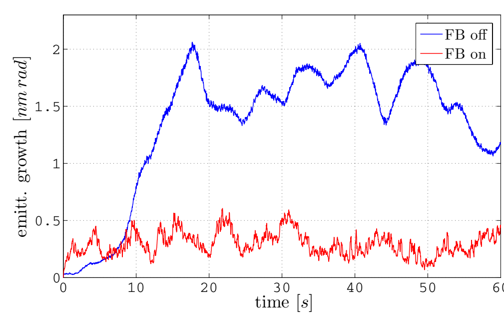

Figure 6: Emittance development over time, due to the effect of ground motion (ground motion model B [6]) without (blue) and with feedback (red).

very well and can keep the error of $\boldsymbol{R}$ below 13 %. This method brings the additional advantage of saving downtime in which normally $\boldsymbol{R}$ has to be measured. Also the optimization algorithm that fits $G(z)$ to the measured ground motion properties works very well. To let the optimization work on-line and independently additional robustness checks have to be performed.
The feedback controller keeps the emittance growth at a constant level of about $0.3\,nm\,rad$. Compared to older designs [7], it has the advantage, that it estimates every QP displacement directly. This makes it easier to combine it with other sensor data, such as from geophones. However, further work is necessary to optimize the performance and verify the robustness of the approach.

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