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Using multiple pickups for transverse feedback systems and optimal pickups–kicker placement for noise power minimization

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ABSTRACT

We propose a new concept to use multiple pickups for estimating the beam displacement at the position 90° before the kicker is activated. The estimated values should be the driving feedback signal. The signals from the different pickups are delayed such that they correspond to the same bunch. Subsequently, a weighted sum of the delayed signals is suggested as an estimator of the feedback correction signal. The weighting coefficients are calculated in order to achieve an unbiased estimator, i.e., the output corresponds to the actual beam displacement at the position 90° before the kicker for non-noisy pickup signals. Furthermore, the estimator must provide the minimal noise power at the output among all linear unbiased estimators. This proposed concept is applied in our new approach to find optimal places for the pickups and the kicker around the accelerator ring such that the noise effect on the feedback quality is minimized. Finally, simulation results for the heavy ions synchrotrons SIS 18 at the GSI are shown.

1. Introduction

Transversal coherent beam oscillations can occur in synchrotrons directly after injection due to errors in position and angle, which stem from inaccurate injection kicker reactions. Furthermore, there is always an increasing demand for higher beam intensities. This leads to stronger interaction between the traveling beam and accelerator objects, which increases the potential of coherent transversal instabilities. Thus, beam oscillations will occur when the natural damping becomes not enough to attenuate the oscillations generated by the coherent beam-accelerator interactions.

Beam transversal oscillations lead to emittance blow up caused by the de-coherence of the oscillating beam. This de-coherence is caused by the tune spread of the beam particles. The emittance blow up deteriorates the beam quality since it reduces the luminosity [1,2]. Therefore, beam oscillations must be suppressed in order to maintain high beam quality during acceleration.

A powerful way to mitigate coherent instabilities is to use a feedback system. A Transversal Feedback System (TFS) senses instabilities of the beam by means of Pickups (PUs), and acts back on the beam through actuators, called kickers [3,4]. The feedback correction signal applied by the kicker must have a 90° phase advance with respect to the betatron oscillation signal at the kicker position in order to have a damping impact. This can be achieved by passing the signal of one PU through a feedback filter, e.g., FIR filter with suitable phase response at the fractional tune frequency, with proper delay [4]. This introduces basically extra turns delay depending on how many taps the filter consists of. In [3], an approach was proposed to calculate the horizontal and vertical beam displacements at the position with 90° phase difference before the kicker, using PUs located at two different positions along the accelerator ring for each of the horizontal and vertical directions. The reason for requiring PUs at two different positions for defining the beam trace space is that only beam displacements from the ideal trajectory can be measured by PUs, but not the angles of the beam.

In general, the signals at the PUs are disturbed by noise. The Signal-to-Noise power Ratio (SNR) can be unacceptably low or not high enough. This is the case especially for lower currents where the beam is getting corrected by a big noise portion during the feedback. That will worsen the feedback correction quality as it leads to beam heating [5] and emittance blow up.

In this work, we address a new approach for mitigating noise at the PUs using more than two PUs at different positions to estimate the feedback correction signal for the kicker position, which has 90° phase difference from the betatron motion at this position. This is done by calculating a weighted sum of the PUs signals after proper synchronization [6]. The idea here is to have more degrees of freedom by using more PUs to adjust the weights such that the noise power at the estimated signal is minimized, while keeping a correct formula for the beam displacement at the position with 90° phase difference before the kicker position in absence of PUs

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noise. This is the so called Minimum-Variance Unbiased Estimator (MVUE) [7].

Furthermore, we address an approach for finding the best positions to place the PUs and the kicker among all possible free locations around the accelerator ring, which are not occupied by other accelerator devices. The PUs and the kicker should be placed such that the noise generated at the PUs causes the smallest disturbance to the feedback quality. As a metric for the noise disturbance, we use the SNR of the feedback correction signal estimate at the kicker position. The noise power is considered here at the output of the previously mentioned MVUE.

2. System model

For each position along the synchrotron ring, three coordinate axes are defined, which determine the different beam displacements from the ideal trajectory. Fig. 1 shows the transversal directions: x, for horizontal displacement, and y, for vertical displacement. The longitudinal direction axis is marked by s.

The TFS is composed of multiple PUs at different positions along the accelerator ring and one kicker for each transversal direction. The signals from the PUs, which correspond to the transversal beam displacements from the ideal trajectory, are delayed accordingly, such that they correspond to the same bunch at every sample. The driving signal at the kicker is digital filtered version of the weighted sum of the delayed signals. A block diagram of the TFS is shown in Fig. 1.

Let x_i be the signal at the pickup $\mathtt{PU}_i$, which is located at the position s_i along the accelerator ring. This signal corresponds to the actual beam transversal displacement $\tilde{x}_i$ (either horizontal or vertical) at s_i perturbed by a noise term z_i, i.e.,

$$x_i = \tilde{x}_i + z_i. \tag{1}$$

In vector notation, one can write

$$\mathbf{x} = \tilde{\mathbf{x}} + \mathbf{z} \tag{2}$$

where $\mathbf{x} = [x_1, x_2, \ldots, x_M]^T$ denotes the vector of signals for the M PUs, $\mathbf{z} = [z_1, z_2 \ldots, z_M]^T$ denotes the noise vector from the PUs with the covariance matrix for unbiased noise given by

$$\mathbf{R_{zz}} = \mathbb{E}\{\mathbf{z}\mathbf{z}^T\}. \tag{3}$$

In Eq. (2), $\tilde{\mathbf{x}} = [\tilde{x}_1, \tilde{x}_2 \ldots, \tilde{x}_M]^T$ denotes the actual beam displacements vector at the PUs positions $s_1, s_2, \ldots, s_M$.

The noise part in the signal can be caused by different sources, e.g., thermal noise generated by the PUs electronics and disturbances from other devices. Thermal noise can be modeled as white noise spectrally shaped by the front end electronics of each PU. This noise part is basically uncorrelated for different PUs. The PUs can produce different thermal noise powers when they are not similar, or placed in different environments, like in cryostat or room temperature. The disturbance at the PUs depends on the locations of the PUs, and could be correlated between some PUs. This noise contribution could have a narrow-band or wide-band spectrum, depending on the disturbers.

The beam displacement at the position s_k located 90° before the kicker can be estimated using the signals x_{i_1} and x_{i_2} of the PUs located at s_{i_1} and s_{i_2}, respectively, where $i_1, i_2 \in \{1, 2, \ldots, M\}$. According to the vector summation approach introduced in [3], the feedback correction signal for the kicker position can be expressed by

$$\begin{aligned}\overline{x}_{i_1 i_2} &= \alpha_{i_1} x_{i_1} + \alpha_{i_2} x_{i_2} \\ &= \alpha_{i_1} \tilde{x}_{i_1} + \alpha_{i_2} \tilde{x}_{i_2} + \alpha_{i_1} z_{i_1} + \alpha_{i_2} z_{i_2} \\ &= x_k + z_{i_1 i_2}\end{aligned} \tag{4}$$

where x_k is the actual beam displacement signal at the position s_k located 90° before the kicker, α_{i_1} and α_{i_2} are constants, which

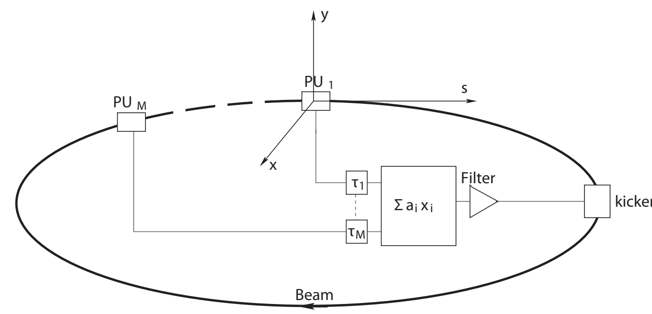

Fig. 1. Block diagram of the TFS.

depend on the lattice functions of the accelerator according to Courant–Snyder Ansatz [8–10]. In Eq. (4), $z_{i_1 i_2}$ denotes the noise part in the estimate of the feedback correction signal.

The noise-free signals at each PU for each bunch are sinusoidal with the fractional-tune frequency with different phases, considering a linear lattice. Therefore, the turn-wise weighted sum of these signals will give a sinusoidal signal with the same frequency, where the phase and amplitude are proportional to the summation weights. In practice however, only kicking on the second or a later turn is feasible. This kicking delay will only affect the required phase shift, and hence the weighting factors.

3. Optimal linear combiner

In order to mitigate the disturbing noise part in the estimation of the feedback correction signal at the kicker position, we address a new approach to calculate an optimally weighted sum of the signals from multiple PUs to be the feedback correction.

The idea of this approach is to filter out the noise from the PU signals by estimating the beam displacement at the position s_{k90} located 90° before the kicker as a weighted sum of the signals from M PUs, i.e., three or more. The weighting coefficients must be calculated in an optimal way such that the power of the noise part at the estimator output signal is minimized and the weighted sum of the actual beam displacement at the PUs positions without noise corresponds to the actual beam displacement at the position s_{k90}.

The optimization problem can be formulated as follows:

$$[\hat{a}_1, \ldots, \hat{a}_M] = \underset{a_1, \ldots, a_M}{\operatorname{argmin}} \, \mathrm{E}\left\{\left|\sum_{i=1}^{M} a_i z_i\right|^2\right\} \tag{5a}$$

$$\mathtt{s.t.} \quad \sum_{i=1}^{M} a_i \tilde{x}_i(t) = x_k(t), \quad \forall t \in \mathbb{N}. \tag{5b}$$

This is a convex optimization problem and can be reformulated as

$$\mathbf{a}_{opt} = [\hat{a}_1, \ldots, \hat{a}_M] = \underset{\mathbf{a}}{\operatorname{argmin}} \mathbf{a}^T \mathbf{R_{zz}} \mathbf{a} \tag{6a}$$

$$\mathtt{s.t.} \quad \mathbf{a}^T \mathbf{b_r} = 1 \tag{6b}$$

$$\mathbf{a}^T \mathbf{b_i} = 0 \tag{6c}$$

where $\mathbf{b_r} \in \mathbb{R}^M$ and $\mathbf{b_i} \in \mathbb{R}^M$ are the real and imaginary parts of the phasors of the PU signals, respectively. The betatron oscillation at the position with 90° phase advance with respect to the kicker is considered here as a reference for the phasors.

Many iterative methods exist to solve such a convex optimization problem efficiently. However, a closed form solution would be more preferable since this solution will be applied on a later approach with exhaustive search nested iterations.