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# STATUS OF TIME-DOMAIN SIMULATION FOR THE FAST ORBIT FEEDBACK SYSTEM AT THE HEPS

Yuanyuan Wei†, Xiyang Huang, Zhe Duan, Yi Jiao
IHEP, CAS, Beijing, China

*Abstract*

High Energy Photon Source (HEPS) is a complex designed at ultra-low emittance. Fast orbit feedback system is proposed to meet the requirement of beam orbit stability at sub-micron level. In this paper, we present our work on setting up an orbit feedback process combined with noise model, system modelling and particle tracking in time-domain. RF phase parameter is adjusted together with fast correctors to mitigate the orbit fluctuation due to energy vibration. The preliminary results are shown here. By the following optimization, we hope to provide an effective tool to specify and configure the FOFB system with the simulation.

## INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, 1360-m, ultralow-emittance storage ring light source in Beijing, China. The emittance of storage ring is 34-pm. The orbit stability for the beam that has extremely small transverse dimensions is very essential, especially in the vertical plane for plat-beam mode ( $\kappa = 0.1$). Generally, the sources that impact orbit stability can be grouped as long-term drift (> 0.01 Hz) and short time-motion (0.01 Hz-1 kHz). The requirements of orbit stability for HEPS based on 10% of beam size are list in Table 1.

Table 1: The Stability Requirements

| Short time (0.01-1000 Hz) | Orbit (µm) | Divergence (µrad) |
|---|---|---|
| Horizontal | 0.94 | 0.2 |
| Vertical | 0.27 | 0.06 |

Fast orbit feedback system (FOFB) for HEP is designed to supress the short time motion at the rate of 22 kHz. The effective closed-loop bandwidth is supposed up to 500 Hz. In this paper, we will focus on the short time stability, and present our progress on time-domain simulation software that is integrated with noise model, performance system model and beam dynamic calculation to configure the specifications of the performance system and evaluate the effectiveness of the feedback system.

Because of the high sampling rate, open-loop bandwidth should amount to nearly 10 kHz. Fast correctors including magnets, power supplies and vacuum chambers need special design. For HEPS， four pairs of fast correctors are located near two straight sections and two BLG magnets respectively in one super-period. Totally, 8 ×24 fast correctors with solid cores are available for FOFB. The strengths of fast correctors are 0.4 mrad, which are used for both normal orbit correction and fast orbit correction.

## FEEDBACK STRUCTURE

Figure 1 shows the structure of the orbit feedback system. The beam orbit with noise is measured by BPM, the orbit distortion respect to golden orbit is multiplied by inverse of response matrix $R^{-1}$ to obtain the setpoints of fast correctors after PID regulating and the performance system response to supress the noise and keep the orbit stable. To implement the simulation, the study is separated into three parts: noise model, performance system modelling and the time-domain feedback code development.

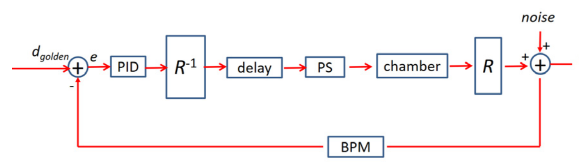


Figure 1: Structure of the orbit feedback system.

## NOISE MODEL

To achieve the required level of beam stability, ground vibration, power supply noises of magnets contribute the fundamental tolerance. In addition, voltage noise of RF system dominated by AC line will cause beam energy vibration that also result in orbit motion in the dispersion area. Applying these noise models, the orbit fluctuations can be simulated turn-by-turn using particle tracking method.

### *Ground Vibration*

The vibrations of magnets affect the behaviour of the beam. The magnet vibration is strongly related to the ground vibration. For HEPS, we have performed measurement to obtain the ground vibration spectra. The result shows ground noise has $1/f^n$ PSD dependence with n close to 4 in the frequency range from 1 Hz to 1000 Hz [1] as shown in Fig. 2. The RMS amplitudes in the horizontal and vertical plane are 22.8 nm and 22.5 nm respectively.

Ignoring the effects of supporting system, we assume the different magnets follow the same spectrum behaviour as the ground vibration but the motions are uncorrelated in the simulation. The magnet vibrations are modelled by a group of sine functions combined the frequency from 1 Hz to 100 Hz with random phase for different magnets. The integrated amplitude of the ground vibration is 25 nm which can be controlled by special slab design. The beam motion will be amplified compared to the ground vibration through magnets, and the orbit fluctuation is simulated by applying

† weiyy@ihep.ac.cn

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the noise model as the misalignment of the quadrupoles using AT code. The ground vibration related orbit motion in horizontal plane is shown in Fig. 3.

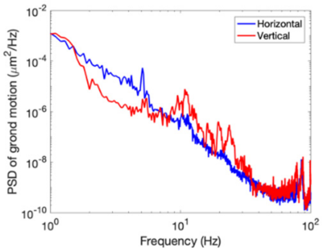


Figure 2: Ground vibration spectra for HEPS.

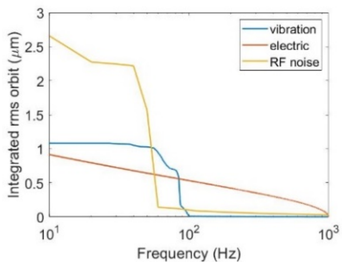


Figure 3: Cumulative RMS motion of noise model in horizontal plane.

## Power Supply Noise

Electrical noise that mainly comes from the ripple of power supply is frequency dependent, and can be attenuated by the solid core of magnets and vacuum chamber. According to the empirical electrical noise spectra, and assuming the magnets are powered independently, we apply the amplification factor and the power supply stability requirements of different types of magnets to evaluate the orbit fluctuation. See the paper [2] in this proceeding for the detail.

## RF Noise

Three fundamental cavities and two harmonic cavities are adopted in storage ring of HEPS. The accelerating voltage or phase noise of RF system is mainly dominated by AC line. In longitudinal plane, the RF noise will change the longitudinal parameters including beam energy, energy spread and bunch length. In transverse plane, the RF noise will affect the orbit stability. Studies [3] show the lines at 50 Hz and its harmonic frequency play the most important role on beam stability related to RF noise as shown in Fig. 4. The yellow line in Fig. 3 shows the orbit motion corresponding the 0.1 degree of RF phase noise.

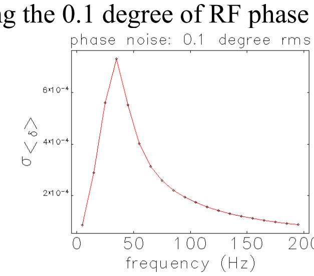


Figure 4: Energy vibration due to 0.1 degree of RF phase noise.

# PERFORMANCE SYSTEM MODELLING

The fast correction magnet with iron core can ensure enough correction ability, but the eddy current effect caused by the magnetic field of the correction magnet and the vacuum chamber will have a certain attenuation in the amplitude of the magnetic field for different frequencies, and a certain hysteric effect in the phase. The characteristics of a system can be described in terms of the ratio of its output signal to its input signal, namely the transfer function. To induce the response of the performance system in the simulation, we model the power supply, magnet and vacuum chamber of fast correctors with their transfer functions.

## Vacuum Chamber

We use the transfer function with three poles in Laplace domain to represent the vacuum chamber of fast corrector [4]:

$$B_{int}/B_{ext} = \frac{p_0 p_1 p_2}{(p+p_0)(p+p_1)(p+p_2)} \tag{1}$$

$$p_0^{-1} = \frac{1}{2}\mu_0 \sigma_c b d,\ p_{n>0} = -n^2\pi^2/(\mu_0 \sigma_c d^2)$$

Where $B_{ext}$ is the excitation field, $B_{int}$ is the magnetic field penetrating the vacuum chamber. For HEPS，the conductivity of the Inconel $\sigma_c$ is $7.94 \times 10^5$, pipe radius $b$ is 11 mm, and the wall thickness $d$ is 0.5 mm.

In addition to using the Eq. (1) to calculate the frequency characteristics of the vacuum chamber, we also use CST program to simulate. It can be seen from Fig. 5 that the calculated result from Eq. (1) is in good agreement with the CST result on the amplitude-frequency and phase-frequency curves. Therefore, in the following simulation, we use the transfer function given by Eq. (1) to model the vacuum chamber.

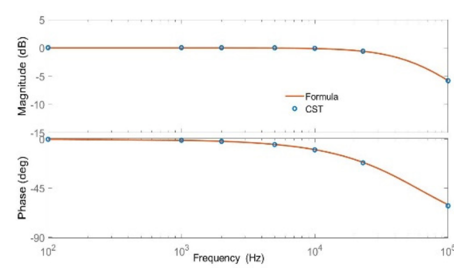


Figure 5: Frequency characteristics of the vacuum chamber.

## Fast Corrector Power Supply and Magnet

The transfer function of first order filter [5] is adopted to model effect between corrector setpoint and magnetic field. To meet the requirement of 10 kHz bandwidth, $\alpha$ is about $5 \times 104$.

$$G_{cor}(s) = \frac{\alpha}{s+\alpha} \tag{2}$$

For the feedback system, the transfer function of orbit error can be written as:

$$G_{dist\_reject} = \frac{1}{1+G_{PI}G_{cor}G_{vam}G_{delay}} \tag{3}$$

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Here, $G_{delay} = e^{-s\tau}$ is the transfer function of system delay τ including BPM electronics delay, control delay of power supply, communication and computation delay. In our study, the delay is less than two feedback period.

## TIME-DOMAIN SIMULATION

The time-domain simulation process based on MATLAB script was developed to evaluate the effectiveness of FOFB.

For the present simulation, ground vibration model and RF phase noise at 50 Hz are considered. Noise models are sampled turn by turn and configured in AT code. Particle distributions at BPMs are calculated by mult-particle tracking which has an equivalent distribution of storage beam initially. The radiation, damping and emission effects are ignored in the simulation, but longitudinal motion is included. By averaging the transverse displacement of all the particles at the same bpm, the orbit motion need to be corrected is obtained.

All the 192 (8 × 24) fast correctors and 384 (16 ×24) BPMs placed at both sides of fast correctors are used in the feedback system. Every 10 turns we calculate the orbit distortion at the 384 BPMs and multiply the inversed response matrix using SVD to obtain the setpoints of fast correctors.

$$\begin{gathered}\Delta z = R\Delta c \\ R = (r_1\, r_2 \ldots r_n\, r_{RF}) \\ \Delta c = (\Delta\theta_1\, \Delta\theta_2\ \cdots \Delta\theta_n\ \ \Delta\varphi_{RF})' \\ R = USV^T\end{gathered} \tag{4}$$

Here, $\Delta z$ is the orbit distortion in the horizontal or vertical plane. In the response matrix $R$, rn means the normal response matrix related to the nth fast correctors, and rRF is the dispersion shape corresponding to RF phase change [6]. In the column vector $\Delta c$, RF phase $\varphi_{RF}$ acts as a corrector, because the fast correctors should not correct the orbit distortion due to energy vibration, setpoints of fast correctors and RF phase can be obtained at the same time.

Ignoring the response time of RF system, the setpoints of fast correctors and RF phase are entered into the performance system. The transfer functions of performance system that includes fast corrector power supply, magnet, vacuum chamber and the delay of the system are discretized with MATLAB function. The outputs of the performance system are set back to the accelerator and one loop of the feedback process is complemented.

To minimize the orbit after correction, PID regulator is necessary in the closed loop. The regulator's coefficients can be initialized using MATLAB PID tuning tool and optimized according to the correction result. The preliminary simulation results are shown in Figs. 6 and 7, which illustrate that the noise considered in this simulation can be supressed effectively with our present design of FOFB system.

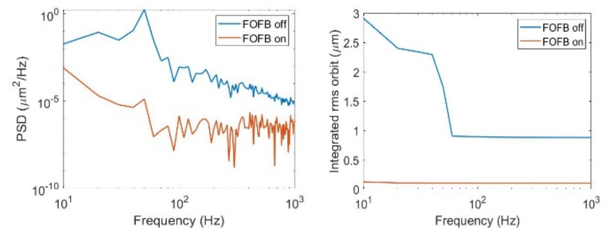


Figure 6: PSD (left) and cumulative RMS motion (right) in horizontal plane with (red) and without (blue) FOFB.

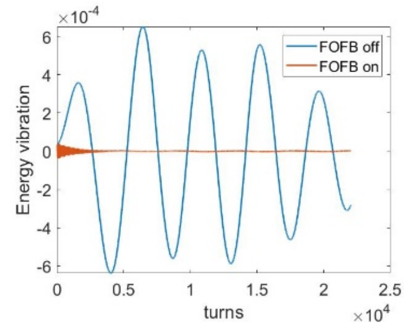


Figure 7: Comparison of energy vibration with (red) and without (blue) FOFB.

## SUMMARY

The simulation preliminarily implemented the process of orbit feedback combined with longitudinal correction, modelled the performance system, and allowed us to evaluate the effectiveness of the FOFB system when consider the main noise sources. We plan to upgrade the simulation by inducing more accurate model, fine regulator tuning, and improved tracking method next, so as to optimize the FOFB system before the commissioning.

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