GLOBAL ORBIT FEEDBACK SYSTEMS DOWN TO DC USING FAST AND SLOW CORRECTORS

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Abstract

Beam orbit stability is a crucial parameter for 3rd generation light sources in order to achieve their optimum performance. Sub-micron stability is now a common requirement for vertical beam position. To reach such performance, Global Orbit Feedback Systems are mandatory. This paper describes the different design approaches for Global Orbit Feedback Systems. A few machines can use a single set of strong correctors. Most of them have their strong corrector bandwidth limited by eddy currents in aluminum vacuum chamber, or power-supply speed together with the required digitization granularity. Then, a second set of fast correctors is required for high frequency correction. But Fast and Slow Orbit Feedback Systems cannot work together with a common frequency range, they fight each other. An earlier solution has been to separate fast and slow systems by a frequency dead-band. This approach does not allow correcting efficiently the orbit shifts due to the gap movements of the increasingly sophisticated insertion devices that are installed on new machines. The different solutions that have been recently implemented are reviewed.

INTRODUCTION

Third generation light sources are built for producing high brilliance photon beams. Brilliance improvements have mainly been achieved by emittance reduction in both planes. The vertical emittance and beta functions define the beam size and divergence, which leads to the beam stability requirements. Commissioned in 1987, Super-ACO had a design vertical beam size of 230 µm in its straight sections. This parameter for NSLS II, to be commissioned in 2013, is ~2 µm, which is 100 times smaller. Position and angular stability requirements, usually one tenth the rms beam size σ_z and beam divergence σ'_z respectively, call for position stabilities of 20 µm for Super-ACO and 0.2 µm for NSLS II. Sub-micron stability is a formidable challenge that can only be achieved by implementing global orbit feedback systems. These systems are increasingly sophisticated in order to combine slow and fast corrections at the required speed and stability levels. Machines presently in operation with only a slow orbit feedback system should be able to profit at reasonable cost of the addition of a fast system using a set of cheap fast correctors that works together with the slow ones. The same scheme will also provide a cheaper solution to the new machines with very small beam sizes.

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BEAM STABILITY REQUIREMENTS

For most beamlines, beam stability implies photon flux stability. They select the photon flux through a slit. The slit defines a beam size aperture for beamlines equipped with a focusing optics and an angular aperture for those equipped with a non-focusing optics. The flux variation is worse with smaller slits. Then the usual requirement $\Delta z/\sigma_z$ or $\Delta z'/\sigma'_z \leq 10\%$ leads to $\Delta I/I \leq 0.5\%$. Let's note that the photon beam size is diffraction limited and the beam divergence is that of the bending magnet or ID photon source; these effects convolved with the electron beam emittance gives the resulting photon beam an emittance larger than that of the electron beam, especially for low energy beamlines. However, for hard X-ray beamlines the electron beam dominates both beam size and divergence.

The effect of the beam position noise on the photon flux depends also on the integration time T_i of the experiment. The position noise components at frequencies higher than $1/T_i$ appear as an emittance growth, not as a photon flux fluctuation. Then the emittance ellipse ε_c describing the electron beam position and angle fluctuations can be added quadratically with the stable photon beam emittance ε_0 for obtaining an effective photon beam emittance ε_{eff}:

$$\varepsilon_{eff}^2 = \varepsilon_c^2 + \varepsilon_0^2 \qquad (1)$$

In this case, high frequencies instabilities do not really affect the stability of the photon flux; they only decrease its intensity in a stable way. One can consider as noise source only the part of the position spectrum that is at frequencies $F < 1/T_i$.

PERTURBATION SOURCES

To fulfil their tight stability requirements, great care is taken in the design and construction of the new machines. Nevertheless, there are still some remaining perturbations to be suppressed by global orbit feedback systems. Perturbation sources can be sorted in decreasing order of their time period [1].

Long Term

With time periods comprised between a few hours and a few minutes, air and cooling water temperatures are important [2]. Changes in air temperature affect the position of Beam Position Monitors (BPMs) and of magnets. In the first case, only the beam position readings are affected. In the latter one, there is an amplification of magnet movements on the beam orbit. Phenomena like sun and moon tides may have an impact of 10 to 30 µm.

Medium Term

Experimental Hall activities often introduce beam orbit perturbations with a time period of a few seconds. Typically, a moving crane can create orbit distortions of 1 to 100 µm peak-to-peak, which is incompatible with user operation. Fast switching magnets for dichroism experiments for example, create perturbations coming from the experimental hall. It can cause position noise of 10 µm and 5 µm respectively in H and V planes [3].

Changes in insertion device settings are also sources of orbit change. Even with feedforward corrections for each ID that strongly reduce orbit changes, perturbations of a few micrometers remain. This is even larger if the feedforward power-supplies involved are not perfectly synchronized [3].

Short Term

Typical Booster cycling frequencies, between 1 and 10 Hz, may affect beam stability. Moreover, vibrations from the ground, cooling water circuits or rotating machinery are transmitted to the vacuum chamber and magnets. It gets amplified at the girder resonance frequencies. The girder vibration modes lie between 10 and 60 Hz, depending on the design. Finally, the 50 or 60 Hz mains and their harmonics usually appear in beam spectra.

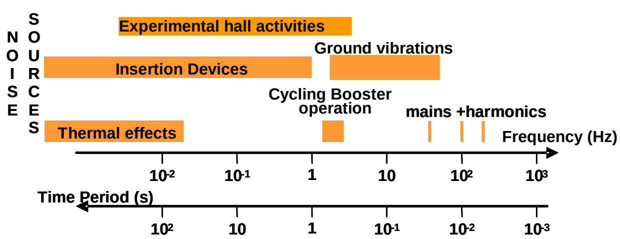

Figure 1: Spectral representation of perturbation sources in a storage ring.

The beam spectrum is machine dependent. A measurement at ELETTRA in shown in Fig. 2. Vibration of quadrupole magnets at 23 Hz as well as the 50 Hz mains frequency and its harmonics are clearly apparent [4]. Fast orbit correction systems are mandatory to suppress those perturbations.

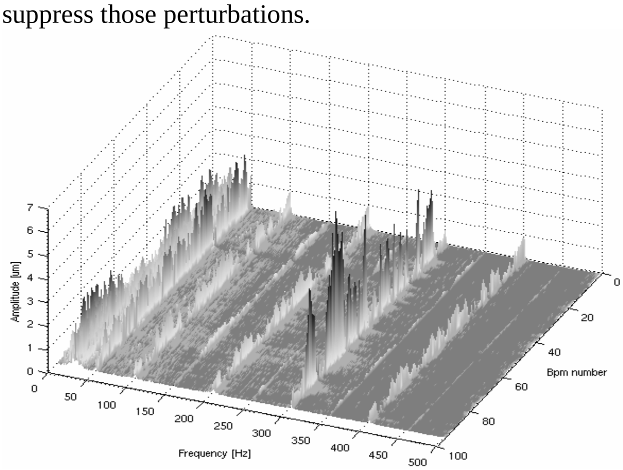

Figure 2: Plot of ELETTRA BPMs amplitude spectra.

GLOBAL ORBIT CORRECTION

The most commonly used algorithm for beam position correction is based on Singular Value Decomposition (SVD) [5]. It provides the inverse response matrix R^{-1} to be used for computing the corrector additional current ΔI:

$$\Delta I = R^{-1} * \Delta U \qquad (2)$$

ΔU is the difference between actual and reference orbits. The correction method is global since it uses all (or a large part of) BPMs and correctors. Local feedback systems are efficient, but a limited number of them can be implemented on a Storage Ring because residual imperfections of a few percent outside the local correction areas add up and spoil the beneficial effects of each local system. Global feedback systems are often preferred with the increasing number of user controlled IDs that perturb the beam orbit.

CORRECTOR SPEED ISSUES

The performance of automatic orbit correction systems, and in particular their bandwidth, will directly depend on the bandwidth of the power-supplies and correctors used for this correction. The important part of the correction spectrum lies between 0 and 150 Hz.

Storage rings are equipped with a set of dipole steering magnets for correcting the closed orbit. Their iron-core makes the magnetic field stronger. Their power supplies must be very stable. In some SR facilities like DIAMOND [6], ESRF-U [7], ELETTRA [8], SLS [9], or SPEAR3 [10], those strong correctors are also used for fast correction. But for one or more of the following reasons, these correctors might not be able to perform fast corrections:

- DAC granularity: On the one hand, the strong correctors must have a large dynamic range for correcting long term alignment drifts; on the other hand, fast corrections need a very fine granularity but over a small amplitude range. As an example, NSLS II stability requirements would imply a granularity of 3 nrad over a full scale of 0.8 mrad if applied to the strong correctors. Choosing two different sets of correctors has been preferred for avoiding power-supplies that at the same time are fast, strong, and have a high granularity [11]. The lower cost is also a motivation.
- Bandwidth limitations: Corrector inductance and power supply rise-time can limit the speed of the correctors. But most often, the limitation comes from the eddy currents in the vacuum chamber that suppress the magnetic field on the beam trajectory. With strong correctors located over aluminum vacuum chambers (or any high conductivity material), those eddy currents will reduce the feedback bandwidth to a few Hertz, incompatible with fast orbit correction. In this case other correctors dedicated to fast correction, can be added. At SOLEIL and NSLS II dedicated power-supplies drive air coil magnets installed

over stainless-steel bellows. In this way, bandwidths over 2 kHz are achievable, as shown in fig. 3.

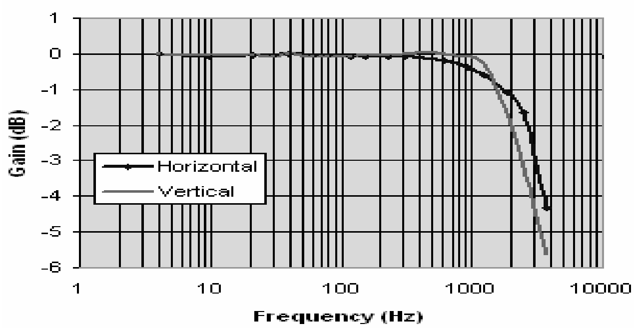

Figure 3: Bandwidth of dedicated power supply + fast air-coil corrector over a stainless steel bellow measured at SOLEIL.

- Historical reasons: older machines with slow corrector power supplies or with correctors installed over aluminium vacuum chambers can implement a fast global orbit feedback at relatively low cost by adding air correctors over stainless steel sections of their vacuum chamber.

FAST AND SLOW ORBIT CORRECTIONS WORKING TOGETHER

We now consider orbit feedback systems with two different sets of magnets for fast and slow corrections. If the two systems are active within a common frequency range they will fight against each other causing quickly a power supply saturation of the weakest system, usually the fast one. A test at SOLEIL showed that the Fast Orbit FeedBack (FOFB) could reach saturation after only ten cycles of the Slow Orbit FeedBack (SOFB). Different approaches have been used over the years, in order to keep up with the increasingly tight stability requirements.

Frequency Dead Band

The first approach was to separate the frequency domains of the 2 systems. This method was used at ESRF, limiting its FOFB bandwidth to 0.1 Hz on the low frequency side [12]. The SOFB had a typical frequency range, from DC to 0.02 Hz. The main advantage is to keep completely independent the two systems. The dead-band needs to be wide enough [13]. The problem with this solution is that all beam spectrum components into the deadband are not corrected and that this frequency range is not always quiet (insertion devices, crane, etc…)

With the increasing number of exotic insertion devices controlled by the users in a wide speed range together with tighter beam stability requirements, this frequency domain cannot be left without correction.

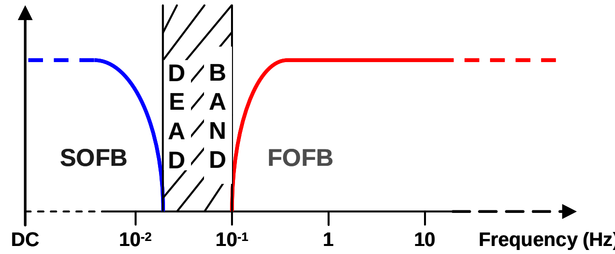

Figure 4: Frequency dead-band between slow and fast orbit feedback systems.

Fast Correction Alone, Down to DC

Then, another approach is to use a Fast Orbit Feedback System alone, with an active frequency range down to DC. It solves the problem of uncorrected perturbations at low frequencies, but presents a limitation due to the relative weakness of fast correctors. They are generally designed to correct small perturbations at high speed (thanks to their low inductance), but have a limited amplitude range of correction (~20 µrad) that brings the correctors into saturation after a few hours or days. The problem can be solved by periodically downloading the DC part of the fast correctors into the slow ones as follows:

Read first the DC-current profile ΔI_{FOFB} of the fast correctors. From this profile and the response matrix R_{FOFB} one computes the difference orbit ΔV:

$$\Delta V = R_{FOFB} * \Delta I_{FOFB} \quad (3)$$

Then this orbit can be corrected with the slow correctors using their inversed response matrix R^{-1}_{SOFB}:

$$\Delta I_{SOFB} = R^{-1}_{SOFB} * \Delta V \quad (4)$$

When applying this new setting ΔI_{SOFB} to the slow corrector, the fast orbit feedback will automatically compensate the transient perturbation and bring the DC-current in its correctors down to 0. This download process can be applied manually or done automatically at a defined rate or after detecting that the fast correctors are close to saturation. This method was used in operation for a few months at SOLEIL with one download a day at the beginning and later a download rate of 10 seconds (fig 5).

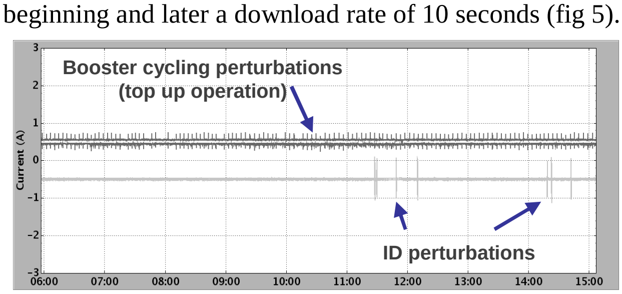

Figure 5: Trend (9 hours operation) on two SOLEIL fast correctors with DC download algorithm.

With this approach, the orbit stabilization efficiency depends on the fast corrector placement. But because of the lack of space, they are generally less numerous than the strong correctors and are installed at the ends of the straight sections where stability requirements are the tightest. Fewer correctors do not correct as many spatial modes and the long term stability in the arcs is affected.

A similar downloading process can be applied periodically to the RF frequency for correcting the orbit circumference drifts. An external process extracts the dispersive part from the corrector pattern and calculates the new frequency to apply to the RF master oscillator. DIAMOND [14] and SOLEIL [15] correct the dispersion part of the orbit in this way, every ~10s.

Interaction between Fast and Slow Orbit Feedback Systems

This approach makes the slow and fast systems work together in the low frequency range. It combines the advantages of the two systems: very good long term stability for every source point and correction in the whole frequency spectrum.

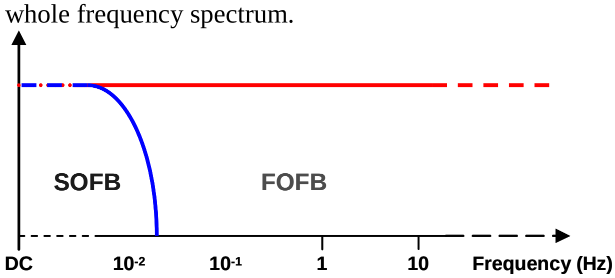

Figure 6: Slow and Fast Orbit Feedback System on a common frequency domain.

As previously mentioned, a common correction frequency range quickly leads to fast correctors saturation. An interaction between the two systems can actually solve the problem.

APS developed a FOFB system that, although not correcting down to DC, has nevertheless a frequency overlap with the SOFB. To make the two systems work together, the slow system predicts the slightly different orbit at its next iteration and transfers it as a new reference to the fast system. As a consequence the Fast System will not see the perturbation created by the slow correction and will not try to compensate it [16]. ALS adopted a similar algorithm, extending the FOFB bandwidth down to DC [13]. But in those two machines, the fast correctors are a subset of the slow ones. At SOLEIL with a set of fast correctors different from the slow ones the combined system was not stable. The different sets of correctors lead to different residual orbits. Even if their contributions are small, those errors accumulate and the current in the fast correctors go to saturation after a few minutes of operation.

The solution presently in operation at SOLEIL consists in combining the orbit prediction algorithm with the DC download algorithm. At each iteration, the SOFB does the following:

- Calculate the new setting $\Delta I1_{SOFB}$ to apply to the slow correctors in order to cancel the difference ΔU between actual and golden orbits:

$$\Delta I1_{SOFB} = R^{-1}_{SOFB} * \Delta U \qquad (5)$$

- Predict the orbit change ΔW after correction:

$$\Delta W = R_{SOFB} * \Delta I1_{SOFB} \qquad (6)$$

Because of the residual orbit, ΔW is not equal to ΔU.

- Calculate the new setting $\Delta I2_{SOFB}$ to apply to the slow correctors to cancel the DC part of the fast corrector currents. From (3) and (4) we have:

$$\Delta I2_{SOFB} = R^{-1}_{SOFB} * R_{FOFB} * \Delta I_{FOFB} \qquad (7)$$

- At the same time subtract the orbit change ΔW from the reference orbit of the FOFB system and apply the new setting ΔI_{SOFB} to the slow correctors given by (5) and (7):

$$\Delta I_{SOFB} = \Delta I1_{SOFB} + \Delta I2_{SOFB} \qquad (8)$$

In short, the slow system corrects two defects: i) the difference between actual and golden orbits and ii) the orbit created by the fast correctors DC component. The FOFB system, running simultaneously, is automatically relieved of the DC part in its correctors and does not fight the slow correction thanks to the periodic change of its reference orbit.

Efficiency

The beam stability benefits greatly from the combination of the two systems. At SOLEIL one of the important improvements has been the long term stability at the bending magnets (BM) source points. Indeed, as the fast correctors are located upstream and downstream of each straight section, the stabilization in the arcs was not efficient enough with the FOFB alone. On the BM photon beam slow drifts up to 15 µm could be observed in the vertical plane. With the two feedback systems working together, those drifts have been reduced to about 2 µm (Fig. 7).

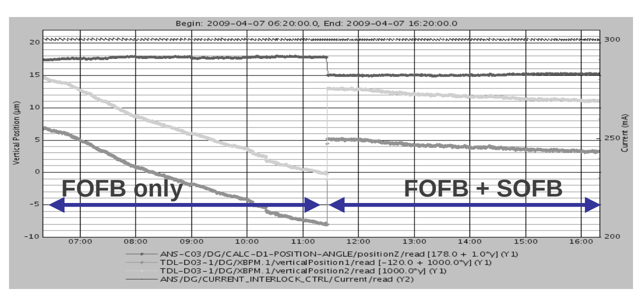

Figure 7: Vertical orbit stability at a BM source point measured by an e-BPM (grey) and a photon-BPM (orange and green).

ORBIT FEEDBACK SYSTEMS STATUS

This section presents a description of the FOFB implementations in several storage rings worldwide (Table 1). Depending on the machine specific criteria (stability requirements, technical possibilities, historical or cost reasons) a solution with one or two sets of correctors has been implemented. It influences the correction bandwidth; it is generally greater with systems with specific fast correctors (150 Hz to 500 Hz) than with systems using strong correctors for fast corrections (60 Hz to 130 Hz). Nevertheless, at lower frequencies both solutions give an equivalent efficiency. One common characteristic for all systems is the continuous frequency range of efficiency from DC to the 0 dB point without any frequency dead band. This has become mandatory with the increasing number of user controlled insertion devices installed on today's light sources.

Table 1: Fast Orbit Feedback implementations in storage rings:

SR Facility	FB type (users operation)	Number of sets of correctors	Bandwidth
ALBA*	Fast	1	DC-130 Hz
ALS	Slow + Fast	1 (fast corr. are a subset of slow ones)	DC-60 Hz
APS	Slow + Fast	1 (fast corr. are a subset of slow ones)	DC-100 Hz
DIAMOND	Fast	1	DC-130 Hz
ELETTRA	Fast	1	DC-150 Hz
ESRF	Slow + Fast	2	DC-150 Hz
ESRF-U*	Fast	1	DC-150 Hz
NSLS II*	Slow + Fast	2	DC-500 Hz
PETRA III*	Slow + Fast or Fast	2	Dead-band or DC-500 Hz
SLS	Fast	1	DC-100 Hz
SOLEIL	Slow + Fast	2	DC-250 Hz
SPEAR3	Fast	1	DC-100 Hz
SSRF*	Slow + Fast	2	DC-100 Hz

* Feedback systems that are not yet commissioned

CONCLUSION

Several machine implemented a scheme with the fast correction performed by strong correctors. Such a scheme applies mainly to new machines in the design phase, but with some conditions on old ones (stainless steel vacuum chambers, power-supplies at high update rate, and laminated corrector yoke). It has been demonstrated that slow and fast orbit feedback systems with different sets of correctors can work together. That solution applies to new machines by solving the power supply granularity problem posed by the increasingly tight stability requirements and also to many old machines to implement fast correctors over stainless steel bellows at the end of the straight sections. Then, it becomes possible for many machines to implement a stability upgrade at a reasonable cost.

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