FAST POSITIONNAL GLOBAL FEEDBACK FOR STORAGE RINGS

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Abstract

Stability of the closed orbit of a storage ring is limited by the stability of the components defining this orbit: magnets position and field values. Measurements of the variation of the stored beam orbit with respect to a nominal orbit and application of orbit correction derived from these measurements can reduce these distortions. The subject of this talk is the implementation of such correction at high frequencies (up to about 100Hz) using global correction schemes.

The basic theoretical aspects of the problem will be presented:

-Global versus local scheme

-Feedback loop dynamics.

The technical problems associated with the implementation of such systems will also be addressed:

-BPM and correctors design

- Feedback loop electronic design

1 INTRODUCTION

Most modern lepton machines have emittances of the order of 10nmrad and 1% coupling. In order to offer optimum performance to their users, storage rings must achieve excellent orbit stability, especially at the source points on synchrotron radiation sources or interaction points on colliders. The requirements on this orbit stability are usually specified in terms of tolerated orbit centroid motion with respect to the beam size. Depending on the local value betatron function, the beam sizes and divergences are 10μm and 1μrad or less. So, in order to take advantage of such small beam size, we aim at controlling the orbit with micron accuracy at these specific locations. In the case of light sources the problem is more demanding due to the greater number of source points spread all over the ring compared to the few interaction points of colliders. The reduction of the orbit distortion in the rest of the machine is also mandatory in order to achieve these emittance figures, to obtain a good lifetime and to protect the vacuum chamber against the synchrotron radiation thoug in the latter case the stability requirements are slightly less stringent [1]. Various sources of perturbation of the closed orbit can be found on most machines [2][3]. Below .1Hz we will find ground motion due to seasonal or tidal causes and thermal effects. They will be dealt with by machine realignements (seasonal effects) and beam position measurements followed by closed orbit corrections using correctors dipoles magnets[4]. Between .1Hz and 100Hz, the perturbation will come from the ground vibration transmitted by the magnet girders, the water circulation, the AC power distribution. A typical spectrum of these perturbations is shown on figure 4. These additional fast sources of perturbation should be minimised at their source, but the residual orbit perturbation level can still be above 1 μm, even on well designed machines[2][3]. This level is not high enough to spoil the machine tuning but can increase the apparent emittance for the users. These fast residual perturbations can also be reduced by closed orbit corrections but the repetition rate of these corrections poses specific challenging problems for the orbit control.

2 CLOSED ORBIT DISTORTION AND CORRECTION

2-1 Principle

Variations of the position of quadrupoles or sextupoles, tilts of the dipoles orientation, fields fluctuations, will result in the addition of angular kicks to the nominal dipolar fields of the ring. These kicks are compensated by a change in the closed orbit in order to obtain a new closed orbit, where the perturbation kicks effect is compensated by the kicks produced by the offset of the new perturbed beam closed orbit with respect to the quadrupole center as shown on figure 1. To perform a closed orbit correction an orbit measurement is done, using a set of e^- (or photons) BPMs and a set of correction kicks is applied to the beam using correctors dipole magnets in order to cancel the difference between the reading and the desired value.

2-2 Global correction

With this scheme, an adequate number of M BPMs, spread all over the machine are used to measure the orbit distortion. The vector δd of the M beam position offsets is used to calculate a correction vector $\delta\theta$ containing the values of N correction kicks using a M*N correction matrix R^{-1}. $R^{-1}$is deduced from the N*M response matrix R formed by the response of the M BPMs to individual correctors unit kicks. R can be obtained from a theoretical model or from measurements. The calculation of the correction matrix R^{-1} can be done using various methods; The most common method seems to be the Singular Values Decomposition (SVD)[1]; the SVD method is very flexible and does not require R to be square. The adequate number and location of the BPMs and correctors are function of the lattice design, of the space available on the machine, and of the quality of the correction needed. The number of BPMs and correctors used can be very large (224 BPMs and 96 correctors at ESRF for a 32 cells Chassman-Green lattice). However, due to the quasi periodic pattern of a beam distortion due to random kicks, a significant reduction of a distortion can already be obtained using a much smaller number of BPMs and correctors. A rule of thumb is that using a number of BPMs and correctors equal to the tune number of the plane considered, you can achieve a reduction by a factor of 3 to 5 of most random orbit distortions as shown on figure 1

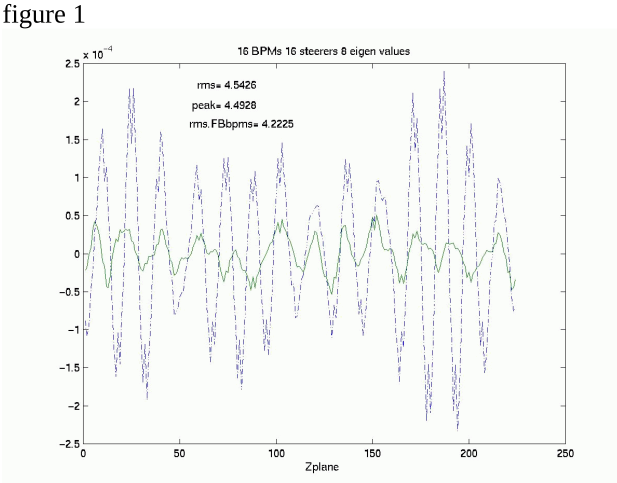

Figure 1: correction of a random vertical orbit distortion on the ESRF lattice with 16 BPMs and 16 correctors.

2-3 Local correction

Since the orbit stability is particularly important at some discrete locations like insertion devices or interaction points, the correction can be aimed at suppressing the orbit distortion only at these location using a closed bump, leaving the rest of the machine uncorrected. Such a scheme requires two BPMs for the orbit distortion measurements in a straight section and four correctors for the local cancellation of both position and angle and the bump closing.

3 FAST CORRECTIONS

3-1 Feedback loop basics

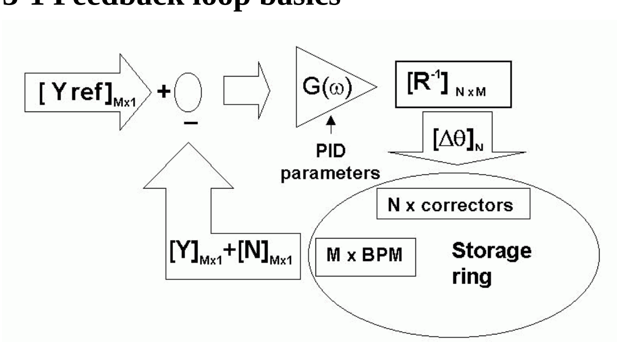

Figure2: Block diagram of a feedback loop orbit

If we control the orbit distortion with the feedback loop of the figure 2, corrected orbit will be given by :

$$\delta c = (\delta d + G.N)/(1+G)$$

with:

Y= measured orbit vector,

Yref = reference orbit vector

δd , δc = (Y-Yref) without and with feedback

G = gain of the corrector, N= noise of the BPMs

A G value as high as possible seems to offer the largest δd/δc damping potential. But if τ, delay in the loop, is not null, at some frequency the phase due to this delay will revert the sign of the correction and the system will be unstable. The delay τ will come from the sampling and multiplexing process in the BPMs, the correction processing time (in a digital correction system) and from the rise time of the correctors field (eddy currents and power supplies rise time). A very popular way to design a stable and efficient corrector is to use a PID corrector [5]. In a PID corrector, G response is a combination of a proportional response with a gain P, integral response with a gain I and derivative response with a gain D; in this way, an very large gain is achieved at low frequencies, the stability of the loop is improved by the proportional part near the cutoff frequency fc, and the derivative gain can improve the step response if necessary. This corrector can be implemented in an analog design as well as using a DSP. The limiting factors in the choice of the I gain which sets the cutoff frequency will be the noise of the BPMs and the delay of the loop. If the noise spectral density of the BPMs is too high, this contribution to δc, integrated up to the cutoff frequency can be higher than the initial orbit distortion, spoiling the effect of the correction.

3-2 Optimisation of the feedback parameters

Let us roughly estimate acceptable values for fc, N(ω) and τ with the motion spectrum of the figure 4: To be useful, a fast feedback system should be able to damp the orbit distortions up to 50Hz, so fc=150Hz at least to have a damping of 3 at 50Hz and τ must be less than 1/(10.fc) = .6ms to have a stable loop with this fc value; and if we aim at a closed orbit reduction below 1µm, the BPMs noise contribution should stay below .3µm over this 150Hz span which requires a noise spectral density N(ω) below 20nm/√Hz. The damping actually achieved will also be function of the spectrum of the initial orbit distortion. For instance , with the spectrum of the figure 4, observed at ESRF, a damping of 3 over the 0 to 200 Hz span could be expected on the initial 2µm wide band distortion at the BPM location with the parameters fc, τ, N(ω) chosen above, assuming a perfect static correction. No increase of the numbers of BPM and corrector will make up for the limitation of the correction accuracy due to the bandwidth limitation, so this figure will be used , in the case of a global feedback, to set the optimum number of BPM and corrector to be used in the dynamic correction. In our case a static damping of 3 to 5 is adequate.

3-3 Local and global scheme comparison for fast corrections

For a good performance of a machine in term of emittance, lifetime, resonance limitation, a slow orbit correction system based on a large number of BPMs and correctors is needed (see 1). The rate of the corrections possible with such a large number of components will be limited (especially by the correctors bandwidth as explained in 4-3). Additional corrections at a higher rate can be needed in a limited number n of discrete locations, for instance at the emission points of a light source. If n is small, the implementation of N additional local correction systems (using 2 x n BPMs and 4 x n correctors) can be the solution. However if n becomes large a fast global scheme using a limited number of dedicated wide band BPMs and correctors is a better solution for the following reasons:

1- The perfect closure of a local bump at high frequency is difficult to achieve due to the different dynamic responses of the four different correctors; so the operation of too many fast local feedbacks will eventually result in some increase of the orbit distortion outside of the bumps and eventually to unstable loops behaviors due to cross talk.

2- As shown in 2-2 and 3-1, the same damping is achieved by a global feedback on the whole ring, using much less BPMs and correctors than local feedbacks, with the same efficiency.

Conclusion: The adequate solution to extend the orbit corrections in frequency above a few Hz is to implement an additional system using a limited number of wide band BPMs and correctors; depending on the number of locations where the correction is needed, this system will be a local or a global feedback.

4 TECHNICAL ISSUES

4-1 General guideline

The number of component (BPMs, correctors, control interfaces) needed for the fast corrections is only a fraction of the number needed for the slow corrections. If the performance required for the fast corrections components cannot be achieved by the slow corrections components without extra cost or compromise on the performance level (principally speed and BPMs noise spectral density), it will be more efficient to implement specific components for this application. If adopted, this separation will require a de coupling of the two systems; different decoupling schemes are possible[1]. The choice of a frequency separation of the slow and fast system can ease the design of the BPMs and correctors as explained below.

4-2 BPMs

4-2-1 Electron BPMs

I will give below examples of difference in the design optimisation of a DC slow BPM and a wideband AC BPM.

1- For slow correction, the wide band spectral noise density of the BPMs output signal is not a major concern to achieve a good resolution, since it is possible to filter this noise with a low pass filter; for a fast BPM, this filtering cannot be applied and this noise density must be kept as low as possible. On the other hand linearity of the position measurements versus beam current is a major concern for DC position measurements; it requires to operate the analog components of the pick up signals processing electronics far enough from their saturation level, which is not the best way to lower the signal to noise ratio at the BPM output. This linearity concern is less important for AC measurements used in a closed loop feedback. The multiplexing scheme with single heterodyne RF receiver is very popular for the processing of signals of the BPMs electrodes. It has the advantage of an easy and accurate absolute DC calibration, good DC measurements reproducibility in a wide current dynamic range and is cheap to implement. These qualities are very much appreciated for DC orbit measurements. However, compared to non multiplexed schemes, its noise figure is at least 6 dB worse, the level of the signals to process in the RF mixer is higher, and the multiplexing frequency must be very carefully chosen in order to avoid unwanted aliasing of high frequency signals (revolution frequency, synchrotron and betatron oscillation frequencies).

4-2-2 Photon BPMs

Due to the smaller space between their electrodes, and to the high synchrotron radiation power available, the photon BPMs can achieve a lower noise spectral density for wide band position measurements than electron BPMs. Dipole emission can only be used for vertical position mesurements; insertion device emission can be used in both planes; but their use in electron beam orbit local correction systems in straight sections is impaired by the pollution of the photon signal of the insertion device by the adjacent dipoles emission. However, for a global vertical orbit correction system, photon vertical BPMs using the dipoles emission would be very good candidates compared to electron BPMs; the high vertical β value at the dipole source point is an advantage, and the resolution of electron BPMs in the vertical plane can be at the limit of what is required on some recent storage rings.

4-3 Correctors magnets and power supply

Given the low delay and high bandwidth required, the correctors must be air cored magnets installed on high resistivity wall vacuum chamber sectors (thin stainless steel wall for instance). Air cored magnets are bulkier than iron core magnets, so their number should be limited to what is required for the fast corrections. If these magnets are used only for the corrections of vibrations without delivering DC currents, this will also relax the power requirements for their power supply. To drive an inductive load, with a flat frequency response and a low delay is not easy. Two solutions are possible: to damp the inductance with a low value resistor and to use an over dimensioned voltage power supply, or to use a PWM switched current power supply[6], with a current control loop optimised for the magnet load. Values of components used on a system in operation at ESRF are given in 4-2.

4-5 Control system

Even with a moderate number of BPMs and correctors (16 BPMs and 16 correctors on the ESRF described below), the calibration and tuning of a loop implemented with analog controllers would be impossible. So the control of the feedback will be done using a digital signal processing technology. CPU boards and programming tools adequate for this application are widely available due to the extensive use of DSPs in the industry. The signals transmission between the BPMs , the correctors and the controller can be analog or digital; the choice will depend mostly on the size of the machine; a popular device for the digital data transfer for this application is the reflexive memory [7][8] but others approaches are possible [9].

5 AN EXEMPLE OF DESIGN: THE ESRF VERTICAL GLOBAL FEEDBACK

5-1 Orbit correction requirement

The ESRF storage ring is a high brilliance source with low emittance values (ε_x =4.10^{-9}m.rad and ε_z=4.10^{-11} m.rad) and generates Xray from insertion devices installed on 5 m long straight sections. With β_x=36m and β_z=2.5m in the center of the high horizontal beta straight sections, the rms beam sizes at the BPM locations on both ends of the straight sections are σ_x= 380µm and σ_z= 14µm. The parasitic motion of the beam due to slow drifts or high frequency vibrations of the quadrupoles support girders must be kept at low enough values to avoid spoiling this emittance figure. We observe two kinds of motions: very slow drifts and vibrations at 7Hz, 30Hz and 60Hz as shown on the figure 4. The amplitude of these vibrations at the ends of these straight sections is 12µm rms horizontally and 2µm rms vertically. The slow drifts are corrected every 30seconds by a global correction method using the measurements made over the whole machine by the 224 BPMs of the closed orbit measurement system [4]. These vertical vibrations are smaller compared to the horizontal vibrations, but not negligible compared to the incoherent motion due to the vertical emittance. We have added a vertical fast global orbit correction system to damp these vibrations in the vertical. In the design of this system we have used the approach exposed in this talk.

5-2 System configuration

Since the vertical tune value is 14.39 this system uses 16 BPMs and 16 correctors to correct the orbit at a 4.4KHz rate in order to provide an extra damping in the 10^{-2} to 200Hz frequency range. The layout of the system is shown on figure 3.

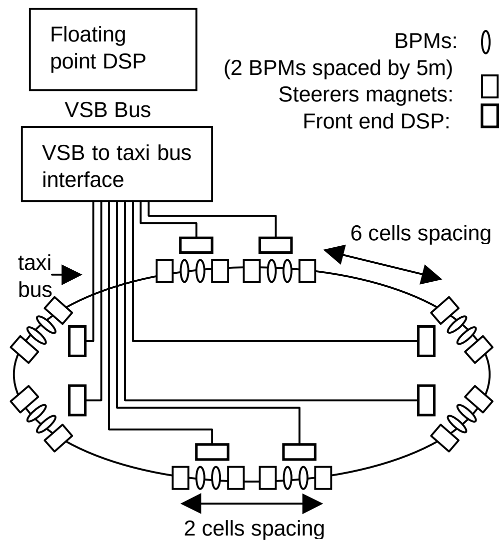

Figure 3: Layout of the ESRF global feedback system.

5-2-1 Beam position measurement

The beam positions are measured using capacitive electrodes installed at both ends of the straight section.. The electrode signals are detected with an RF multiplexing system; as pointed in 4-2-1 it is easy to implement though it does not have the lowest potential noise figure. However special attention has been paid to the noise of the electronics allowing to achieve a resolution of 20nm/√Hz over the full operation intensity range from 5mA (in single bunch) to 200mA . Special features of these BPMs are: impedance matching of the electrodes by resonant RF transformers, 4.4KHz multiplexing synchronized with the beam revolution, low noise amplifiers and gain control [9].

5-2-2 Orbit corrections

The correction kicks are produced by sixteen air coil steerer dipoles. The stainless steel vacuum chamber at the steerers location is 2mm thick giving the beam a flat frequency response to the magnet field up to 1KHz; the steerers inductance is 40mH. The steerers are powered by wide band power amplifiers and are able to produce 4µradian/A kicks in a 1KHz bandwidth. The amplifiers are voltage controlled bipolar PWM current mode switched power supplies developed at ESRF. They can produce a peak voltage of 100V and a peak current of 5A. The total contribution of eddy currents and power supply rise time to the loop delay is .25ms.

5-2-3. Digital signal processing hardware

The digital signal processing is implemented as shown on figure 3. The corrections are computed at a 4.4 KHz rate by a LSI DBV44 VME board housing a TI C40 floating point DSP and a VSB bus. The datas are transmitted on eight optical digital data links to eight front-end VME crates developed at ESRF [11]; these crates carry IP modules format DACs and ADCs, and are controlled by front end fixed point AD2600 DSP for the data preprocessing and transfer control. The data transfer at both ends of the optical fibers is done with "taxi bus" data link drivers implemented on IP modules also developed at ESRF. The data acquisition and transfer to and from the main DSP takes 100 µs leaving 125 µs for the main algorithm execution. The VME bus itself is not used for any fast data transfers.

5-3 Correction calculation

With the 16 positions we calculate a correction vector using the matrix of the response of the feedback BPMs to each steerer, inverted using the SVD method. We use 8 eigen vectors. This correction vector is used to compute the actual correction applied to the beam using the previous correction values and a proportional integral iterative algorithm (PID type). In addition, the correction is cancelled at very low frequency (10^{-2} Hz) to decouple the fast orbit correction from the slow orbit correction. The repetition rate of the BPMs measurements and correction calculation is 4.4 KHz, a convenient sub harmonic of the 355 KHz beam revolution frequency. These dynamic parameters have been chosen as explained in 3-1: We aim at a cut off frequency fc=150Hz; this fc value demands a total delay τ of less than .6ms. The delay in the correctors is .26ms. We perform the position acquisitions, correction calculation and apply the correction inside a 4.4 KHz clock period. The delay due to the multiplexing in the BPMs is τ_{mux}=.175ms and the delay due to the correction computation and data transfer time is τ_{cpu} =.225 ms so the total loop delay is τ = .65 ms .

5–4 Correction effect

The figure 4 shows the spectrum of a dipole emission beam motion due to fast orbit distortions measured 25 m away from the source with feedback off and on. Without feedback, the main perturbation is a 7 Hz line due to the mechanical resonance of the dipole girders as pointed out in 1. With the feedback on, as shown in figures 4, the amplitude of this line is reduced by 10 dB and the wide band motion integrated over 140Hz is reduced by 6 dB.

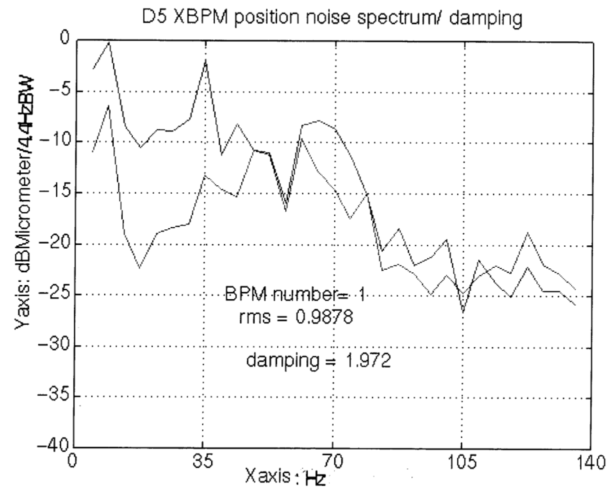

Figure 4: spectrum of the ESRF beam vertical motion with feedback off and on (5dB/div, 140Hz span)

6 CONCLUSION

The principle of the fast orbit corrections is not original but the efficiency of this scheme at high frequency and on very small orbit distortion requires a careful optimisation of the performances of its different components. The key parameters in such a system according to our experience are the noise of the BPMs, the bandwidth of the correctors, the number and location of the BPMs and correctors and the delay in the loop.

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