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REAL TIME CLOSED ORBIT CORRECTION SYSTEM

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Abstract

We describe a global closed orbit feedback experiment, based upon a real time harmonic analysis of both the orbit movement and the correction magnetic fields. The feedback forces the coefficients of a few harmonics near the betatron tune to vanish, and significantly improves the global orbit stability. We present the result of the experiment in the UV ring using 4 detectors and 4 trims, in which maximum observed displacement was reduced by a factor of between 3 and 4.

1. Introduction

Stability of the electron orbit is critical for the utilization of a low emittance storage ring as a high brightness radiation source. In this note we discuss a global orbit feedback system [1] based upon an harmonic analysis of the orbit movements and the correction magnetic fields. This harmonic feedback system cancels the Fourier components of the orbit nearest to the betatron tune. Harmonic orbit correction is an effective technique for eliminating global orbit distortion in storage rings resulting from inevitable magnetic field errors distributed around the ring. To our knowledge, this approach has not been previously applied dynamically to eliminate orbit fluctuations arising from time varying magnetic field errors.

In this paper, we discuss an harmonic feedback system constructed and tested on the 750 MeV VUV ring of the NSLS, implemented on a real time basis using relatively simple electronics. The Fourier analysis is done by a simple linear analog network. The input voltages are proportional to the orbit displacements at the detectors, and in real time the output voltages are proportional to the desired Fourier harmonic coefficients. The feedback does not force the displacement to be zero at the detectors, but forces the coefficients of a few harmonics nearest the betatron tune to vanish.

The vertical betatron tune of the VUV ring is 1.20, hence the feedback system was designed to correct the sine and cosine components of the first harmonic of the orbit fluctuations. The orbit deviations were measured at four symmetrically located RF pick-up electrodes (PUE's), and the correction was implemented using four trim dipole magnets, wired into two families driving the sine and cosine of the first harmonic of the orbit. Orbit movement was observed to be reduced by a factor of 3 all around the ring, and by as much as a factor of 10 at certain locations. In the following, we discuss the theory, implementation, and test results for an harmonic feedback system on the VUV ring.

Existing feedback systems [2] to improve orbit stability have been based upon local orbit bumps for an individual user. For a large facility such as the NSLS, which will eventually have 100 beamlines, the installation of a local bump feedback system for every beamline would be both costly and impractical. The harmonic feedback system described in this note can provide improvement in orbit stability for all beamlines simultaneously, using electronics no more complex than that required for a single local feedback system. Local feedback can still be used for those experiments requiring the tightest orbit tolerances. Indeed, the global harmonic feedback offers advantages which will complement and enhance the performance of local feedback loops. Cancellation of the principal harmonics makes the most efficient use of the available trim dipole magnet strength, which sets a significant limit on the dynamic range of local feedback loops. Also, the harmonic analysis of beam position monitor signals results in significant rejection of detector noise.

2. Theory

The feedback system we shall discuss utilizes 4 PUE RF detectors uniformly distributed about the ring with their Courant-Snyder phases separated by $\pi/2$. The 4 correctors used are also uniformly distributed with $\pi/2$ phase separation. Since the vertical tune of the VUV ring is 1.20, the orbit motion is dominated by the first harmonic. The feedback system provides for the correction of the sine and cosine components of the first harmonic of the vertical orbit fluctuations. A least squares method is used to determine the sine and cosine coefficients by minimizing the sum

$$S = \sum_{i=1}^{4} [\eta_i - a \cos \phi_i - b \sin \phi_i]^2 , \qquad (1)$$

where $\eta_i = y_i/\sqrt{\beta_i}$ is the orbit deviation signal divided by the square root of the betatron function at detector i, and ϕ_i is the Courant-Snyder phase at the detector. Requiring the derivatives of S with respect to a and b to vanish, yields

$$\begin{bmatrix} a \\ \\ b \\ \end{bmatrix} = \mathbf{F} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \end{bmatrix} \qquad (2)$$

where the 2x4 matrix **F** depends only upon the phases ϕ_i at the 4 detectors.

The feedback system is illustrated in Fig. 1. The output of the 4 PUE's are the the input for the Fourier analysis 2x4 matrix network **F**. The outputs of **F** are the two voltages corresponding to the two Fourier coefficients of $\sin\phi$ and $\cos\phi$ for the vertical feedback, when the vertical tune is 1.20. The linear network with 4 x 2 matrix **T** is used to generate different trim current combinations. The 4 elements of the first column of **T** correspond to a set of trims weighted according to $t_i = \cos\phi_i$ while the second column corresponds to a set of trims weighted as $t_i = \sin\phi_i$.

If the input 1 of **T** is applied with a voltage of 1 volt, and the input 2 is grounded, then the output of **T** will be proportional to the first column of **T**, and will excite an harmonic orbit displacement as a linear combination of the sine and cosine. We call this an harmonic orbit, because it has predominantly the first harmonic components. The output of **F** would give the two Fourier coefficients of this orbit. If we switch the two inputs of **T**, then we can measure the

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two coefficients of another linearly independent harmonic orbit in the same way. These 4 coefficients form a response matrix **R**, with the first 2 coefficients as the first column, the last 2 coefficients as the second column. Thus the element R_{11} is the cosine coefficient of the $t_i = \cos\phi_i$ orbit, etc. Once **R** is measured, we can build another 2x2 linear network **M** with matrix $\mathbf{M} = \mathbf{R}^{-1}$, and connect the output of **M** to the input of **T**. We can see immediately that the response matrix between the input of **M** and the output of **F** is now the unit matrix: $\mathbf{RM} = \mathbf{RR}^{-1} = \mathbf{I}$. Thus we have achieved two independent channels, each corresponding to one Fourier component of the orbit, and we can apply conventional servo control feedback techniques to these two channels separately and force the output of **F** to be zero. The servo control forcing the sine and cosine components of the first harmonic to vanish is implemented by the introduction of two elements with large negative gain $-g_1$ and $-g_2$, respectively, as illustrated in Fig. 1. Once the loop is closed, harmonic feedback is implemented in real time.

The networks **F** and **T** are determined theoretically in terms of the Courant-Snyder phases at the detectors. In order that the actual system have two independent channels, we introduce the empirically determined matrix **M** to diagonalize the system. We have found that the network **M** can be determined very accurately by carrying out simple measurements on the storage ring as the feedback system is being installed. The matrix **M** corresponds to a fine adjustment of the system, since the matrices **F** and **T** are quite accurately determined theoretically. In fact, in the UV ring with its four-fold symmetry, we use four detectors each separated by one superperiod. Note that these detectors are separated in phase by $\pi/2$ independent of tune. Deviations of the phase difference between detectors from $\pi/2$ only result from asymmetry of the betatron functions, which is small in the UV ring. The above discussion, of course, also holds for the four trims which are also each separated by one superperiod. Hence the 4-detector 4-corrector system under discussion is quite insensitive to the precise value of the betatron tune and betatron functions.

The matrix networks **F**, **T** and **M** are made of arrays of operational amplifiers, the matrix elements are set by potentiometers. For example, the 4x2 **F** matrix network has 8 potentiometers. Every input or output terminal has its individual zero point offset adjustments, and all the input buffers have test points and output terminals are all zeroed. The value of a matrix is dialed while applying 1V at the input and measuring the corresponding output.

The transfer matrix **R** from the input of the **T** network to the output of the **F** network is measured by exciting the beam with a low frequency (about 5 Hz) sine wave at the inputs of **T**-block. The result is then used to calculate the matrix **M** to decouple the cosine and sine channels. Then the transfer matrix between the input of **M** and the output of **F** is measured as the open loop frequency response matrix. At low frequencies the result is a diagonalized matrix, thus giving two independent channels. A concern is whether the off-diagonal elements remain zero at higher frequency, since differences in eddy current effects from trim to trim may degrade the diagonalization. Tests have shown the diagonalization satisfactory.

3. Receivers

While the harmonic feedback system could be built using photon beam detectors, electron beam position monitors offer certain advantages. Generally electron beam position monitors have a large working range in beam energy, position and current. They measure electron beam position, without the need for producing a focused image of the synchrotron radiation.

The monitors used in the VUV system test are "switched" or multiplexing heterodyne receivers [3] connected to the pickup electrodes normally used for closed orbit measurement [4]. The 212 MHz receivers use a single RF amplifier and detector which is connected in turn to each of the four button electrodes at a pickup station. The connection is made through a GaAs SP4T switch toggled at a 40 KHz rate. The use of a single channel of amplification eliminates the need for ~0.01 dB gain matching of four amplifiers.

After amplification and detection, the four button signal strengths are de-multiplexed and combined by means of operational amplifiers to give the sums and differences necessary to determine the beam position.

An automatic gain control circuit in the amplifier-detector is configured to hold the average of the four button signal strengths constant as the beam current changes. Thus the receiver output voltages depend on beam position only, and not beam current.

Most critical components of this system are common to all four button measurements. Drift in the "electrical center" of the detector could still be caused by a change in insertion losses of the GaAs switch, the cables from the receiver to the pickups, or the pickups themselves. While there is no evidence of uncontrolled drift to date, provision has been made for injection of calibration signals using directional couplers located at the pickup station.

The receivers used in the UV ring harmonic feedback system have ±10 micron equivalent noise in a bandwidth 0-300 Hz, over a thirty-fold range in beam current. Nonlinearity in the position response is dominated by the geometry of the pickup electrode station [4]. The combination is reasonably linear over $-8\ \mathrm{mm} < x,y < 8\ \mathrm{mm}$.

4. Feedback Circuitry, and Bandwidth

The useful frequency response of the steering magnet power supplies (Kepco BOP 20/10) and the silicon steel laminated magnets themselves extend to several kilohertz. For the system tests the receivers and the matrix multiplier circuit blocks, **F**, **M** and **T** in Fig. 1 had wider bandwidths. Eddy currents in the aluminum vacuum chamber set the limits on the open loop bandwidth. The frequency compensation for this effect was lumped in the gain blocks g_1 and g_2. Overall compensated open loop performance targets were:

1. 30 dB gain at DC
2. Unity gain at 100 Hz
3. 20 dB per decade rolloff above 100 Hz

The last requirement was necessary to prevent the magnet power supplies from being driven to their ±20 volt limit by noise at or above 4 KHz. Open loop response measurements were made by exciting the beam with a sine wave at the inputs to the **M**-block and measuring coherent response at the output of the **F**-block. The response can be approximated by a simple pole at 60 Hz but a phase shift corresponding to a 350 microsecond time delay.

The gain blocks g_1 and g_2 (Fig. 1) each consisted of a 40 dB amplifier in series with two cascaded phase-lag networks incorporating a pole at 10 Hz and a zero at 50 Hz. This was followed by a single-pole 400

Hz low pass filter. There was unity gain at 120 Hz with more than 45° phase margin, and a 12 dB gain margin at 180° phase shift.

5. The Feedback Experiments

Tests of the global harmonic feedback system have been carried out on the VUV ring during machine studies periods. The goal of the experiments was to check the improvement in orbit stability attained, and to study the reliability of the system. Since we had only five RF receivers, four of which were incorporated in the feedback circuit, we connected the fifth RF receiver to the switching tree of the orbit measurement system. By switching to the available PUE stations around the ring, we checked the improvement in global orbit stability. The results showed that the maximum displacement was reduced by a factor of 3, and for many locations the improvement was better than a factor of 10.

We also observed the motion of the radiated photon beams at three locations. At port U5, using UDT photodiode position detector, it was observed that at low frequencies (below 20 Hz), the orbit fluctuations were reduced by about 15 dB. At beamline U4, a mirror focuses the image of the electron beam onto an entrance slit of 15 μm size. The beam size is about 100 μm. Around 2 p.m. of December 21, 1988, the beam showed an unusually large random motion with an amplitude of about 100 μm, and a characteristic time scale of 1 minute, so the flux detector behind the slit displayed a 100% intensity fluctuation (see Fig. 2). After we closed the feedback loop, we positioned the slit at the point where the detector output was 50% of the maximum. Here the position dependence of intensity fluctuations were the greatest. The effect of the feedback is shown on the left side of the figure. The noise present with the loop opened is shown to the right.

To check the global improvement, the signal power spectrum was measured at 18 PUE locations, with the feedback loop open and closed. When the NSLS booster is ramping, it induces an orbit deviation at its repetition rate of 0.6 Hz. All around UV ring this movement is observed, and the power spectrum exhibits peaks at 0.6 Hz and its harmonics. We plot in Fig. 3 the amplitude of second harmonic observed at 18 PUE's, comparing the amplitudes with the loop open and closed. The global improvement is clearly demonstrated.

For the long term drift of the beam position, because of the limited number of available detectors, we have only observed the beam motion at 6 locations (4 of them are at the detectors used in the feedback loop) for about 6 hours of quasi-operation period dedicated for user observation, with a fill in the middle of the observation. Even though a trim malfunctioned and oscillated during this period, which should have seriously disturbed the beam, the beam was kept within 30 μm even between fills. The beam movement within a minute was kept within 10 μm.

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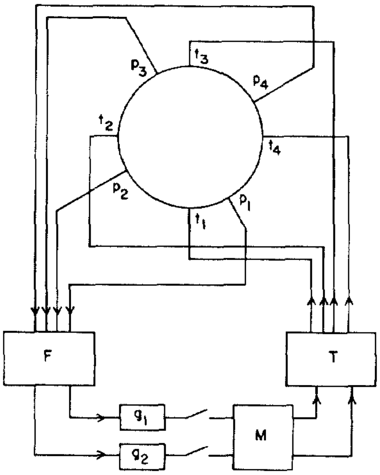

Fig. 1

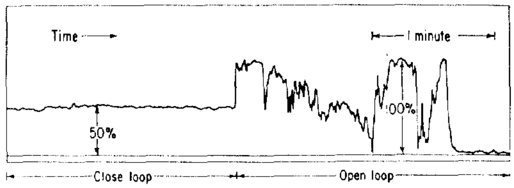

Fig. 2

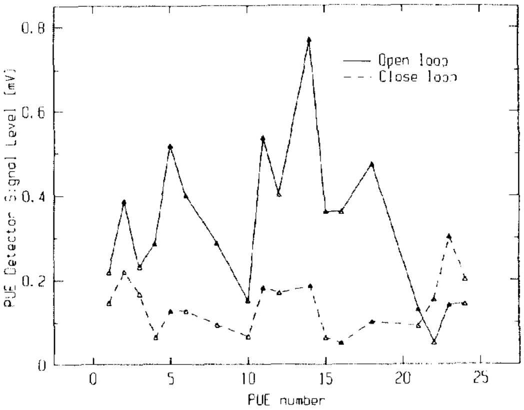

Fig. 3