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EVALUATION OF THE GLOBAL ORBIT CORRECTION ALGORITHM FOR THE APS REAL-TIME ORBIT FEEDBACK SYSTEM

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Abstract

The APS real-time orbit feedback system uses 38 correctors per plane and has available up to 320 rf beam position monitors. Orbit correction is implemented using multiple digital signal processors. Singular value decomposition is used to generate a correction matrix from a linear response matrix model of the storage ring lattice. This paper evaluates the performance of the APS system in terms of its ability to correct localized and distributed sources of orbit motion. The impact of regulator gain and bandwidth, choice of beam position monitors, and corrector dynamics are discussed. The weighted least-squares algorithm is reviewed in the context of local feedback.

1 OVERVIEW

A real-time orbit feedback system has been implemented at APS in order to meet the rms beam stability requirements of 17μm horizontally and 4.4μm vertically in a frequency band up to 50Hz [1]. Both local and global feedback will be provided, with the global system planned to be available for user operations shortly.

The global system uses 38 correctors and has access to up to 320 beam position monitors (BPMs). An additional 279 correctors are available for local feedback. The feedback system is implemented digitally using 20 VME crates distributed around the 40 sectors of the storage ring. A reflective memory network provides synchronous data transfer between the crates, and in particular gives each crate access to data from every available BPM in the ring. Orbit corrections are computed at a 1kHz rate.

2 GENERAL CONSIDERATIONS

In principle, only 38 BPMs are needed to compute the 38 corrector settings, in which case the error at each BPM is corrected exactly. In practice however, using this exact solution can lead to orbit blow-up between the BPMs resulting in ineffective correction of global orbit errors.

The smoothness of the corrected orbit can be improved by singular value decomposition (SVD) to remove small singular values, but this occurs at the expense of the exact correction at the BPMs.

If more BPMs are used in the algorithm, the smoothness of the solution is improved, and the robustness to BPM measurement errors is increased. Since at APS there are many BPMs available to the orbit feedback system, we have chosen to increase the number of BPMs in the algorithm rather than reduce the number of singular values in the correction matrix. The workstation-based slow feedback system [2] uses all available BPMs in its algorithm; there is no penalty in doing this because the correction rate is only 0.1Hz. For the real-time system, on the other hand, there is a trade-off between the correction rate and the number of BPMs sampled. In this case using a larger number of BPMs requires more time be taken up accessing and subsequently processing the additional values.

The present configuration uses 160 BPMs in order to significantly reduce the susceptibility to measurement errors [2]. Ultimately, the same "despiking" algorithm used in the slow feedback system [2] will also be implemented in the real-time system.

3 CORRECTION OF DISTRIBUTED SOURCES

Dynamic orbit errors are generated by many sources distributed randomly around the storage ring. Ground vibration is assumed to couple principally through the quadrupole triplets. The resulting orbit motion can be analyzed in terms of SVD modes. Most of the energy appears in a relatively small number of modes. Up to 38 modes can be corrected with the APS real-time global system.

3.1 Measured SVD Modal Content

The SVD modal content of the APS random orbit motion has been measured using the real-time feedback system by examining the orbit power spectrum. Dynamic orbit errors were corrected with the real-time feedback system using inverse response matrices containing different numbers of singular values. The resulting power spectral density at x-ray source points was measured as a function of the number of singular values retained.

Results from the measurement are presented in Figure 1, where the residual power spectral density is shown as a function of the number of singular values retained in the correction matrix. It is clear there is a large effect from including relatively few singular values and a continued improvement as more singular values are included. Results are comparable with predicted SVD modal content [3].

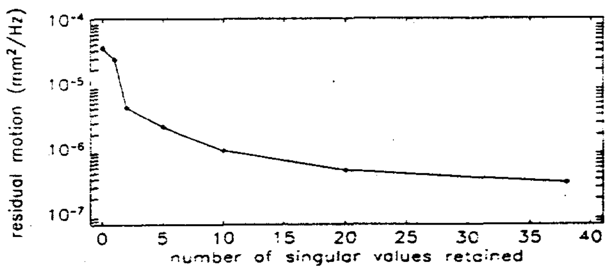

Figure 1: Residual uncorrected orbit at 1Hz vs. number of singular values retained.

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3.2 *Regulator Gain*

The fact that some orbit motion remains uncorrectable means that the feedback system sees a noise floor well above the noise floor of the BPMs themselves. It can be shown that each mode is attenuated with the full gain of the regulator, but once the correctable modes have been reduced below the level of the noise floor, there is little to be gained from further increases in regulator gain.

This effect has been measured at APS using the real-time feedback system. Figure 2 shows the attenuation in beam motion as a function of regulator gain. This shows that just over 20dB attenuation in beam motion is achieved with 28dB of regulator gain, but there is very little improvement in beam motion when the regulator gain is increased beyond this point.

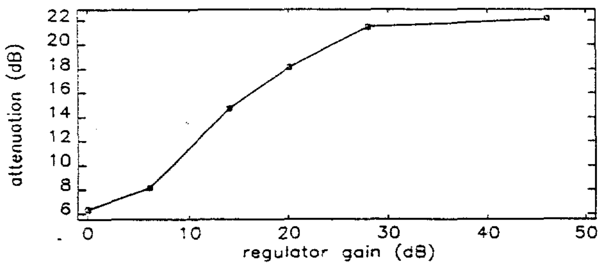

Figure 2: Attenuation of beam motion vs. regulator gain.

3.3 *Regulator Bandwidth*

The system presently operates with a closed loop bandwidth around 25Hz [1]. So far, little effort has been put into optimizing the regulator bandwidth; nevertheless, APS orbit stability specifications are met in both planes down to below 10mHz with the feedback system running.

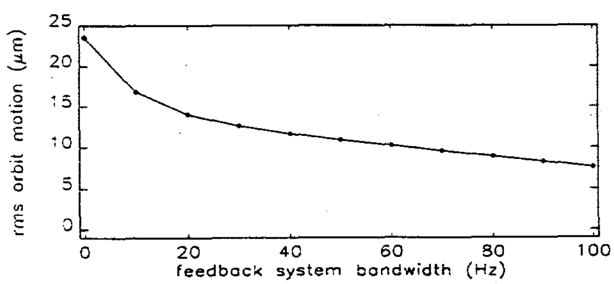

Figure 3: Projected APS horizontal beam motion vs. system bandwidth (10mHz to 100Hz).

Beam stability will improve further as the regulator bandwidth is increased; we expect that the bandwidth could be increased by a factor of two with an improved regulator design.

Yet further bandwidth improvements could be realized by increasing the sampling rate to 2kHz which will be possible when additional processing power is brought on line. Figure 3 shows how the horizontal rms beam motion is projected to improve as the regulator bandwidth is increased. The data is based on the measured power spectral density and includes beam motion from 10mHz to 100Hz [1].

4 CORRECTION OF LOCALIZED SOURCES

Recent observations have shown that the effort applied by the global feedback correctors varies significantly from corrector to corrector. This seems to indicate the existence of localized sources of beam motion, and it is hoped that the observed variations can be used to track down the sources of motion.

Simulations using the accelerator code Xorbit [4] have been run to determine how a localized source of motion influences the corrector power. The pattern of corrections applied by the algorithm is shown to depend on the proximity of the source to the correctors and on the number of singular values retained in the algorithm. In the 'ideal' case where the source of the motion is one of the global correctors themselves, the correction is shown to be highly localized [1].

A more realistic situation occurs when the source of the disturbance is between two correctors. Figure 4 shows the relative corrector power for a simulated source between the correctors in sectors 20 and 21. For the case where all singular values are retained, the source can be localized to within a sector of the machine. Figure 4 shows an Xorbit simulation of the response to an orbit disturbance between the global correctors in sectors 20 and 21.

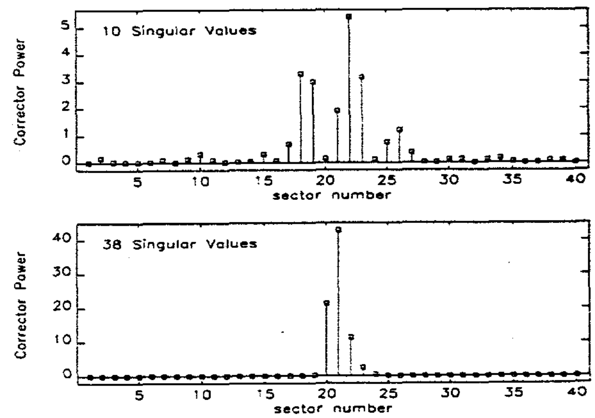

Figure 4: Correction of simulated source in sector 20.

Similar patterns of corrector power were measured in the storage ring with the real-time feedback system running. Figure 5 shows the actual horizontal corrector power by sector, measured in a band around 0.1Hz. It remains to be established whether there exists a localized source of motion at 0.1Hz in sector 37, as indicated by the data.

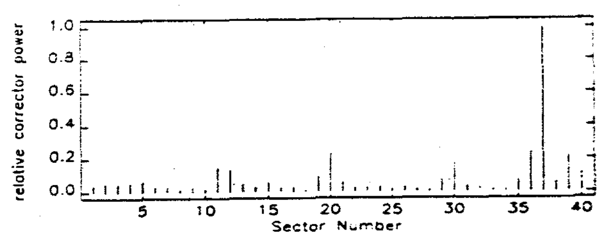

Figure 5: Measured horizontal corrector power at 0.1Hz.

5 LOCAL/GLOBAL FEEDBACK

X-ray beam position monitors are installed on each insertion device and bending magnet x-ray beamline. There are a number of options for including these in a local feedback algorithm in order to control position and angle of the x-ray source points.

An option recently considered is the determination of a global matrix which has the objective of exactly correcting the x-ray source points while simultaneously minimizing the global rms orbit. The algorithm assumes a system with N monitors, of which P must be controlled exactly, while using M correctors, where $P < M < N$. If only the P monitors are considered, then there exists a plane of solutions in M-P dimensions which produces an exact correction at these locations. The M-P degrees of freedom in the solution are available to correct the remaining N-P locations in a least-squares sense.

The algebra associated with this algorithm is straightforward, and the solution can be written in the form of a constant (response) matrix. However, it can be shown that the same numerical solution can be approached using the classical 'weighted least-squares' algorithm, where the P monitors are given a high weighting relative to the remaining N-P monitors. The weighted least-squares method differs from the pseudo inverse algorithm by the introduction of the weighting matrix, and has the form

$$\Delta \underline{c} = [(\mathbf{W.R})^T \mathbf{W.R}]^{-1} (\mathbf{W.R})^T \mathbf{W} \Delta \underline{\mathbf{x}},$$

where $\mathbf{W}$ is a (diagonal) weighting matrix, $\mathbf{R}$ is the forward response matrix, and $\Delta \underline{c}$ and $\Delta \underline{x}$ are vectors of corrector and BPM changes.

The weighted least-squares algorithm offers the capability of achieving simultaneous local and global control using a single global system together with an appropriate response matrix. The capability to do weighting already exists in our orbit correction software [5], and limited tests on the storage ring using x-ray and rf BPMs have established this algorithm does indeed work as described.

6 CORRECTOR DYNAMICS

The APS system is designed to perform both local and global orbit feedback. In order to prevent instabilities from arising, it is necessary to decouple the two feedback loops, either dynamically or spatially.

If all correctors do not have the same dynamics, then it is very difficult to decouple the two loops spatially. This can be shown by considering the error from one iteration of the orbit correction algorithm, in which case the residual static orbit error is given by

$$\mathbf{E} = \Delta \underline{\mathbf{x}} - \mathbf{R}\,(\mathbf{R}_{inv}\, \Delta \underline{\mathbf{x}}),$$

where $\mathbf{R}$ and $\mathbf{R}_{inv}$ are the forward and inverse response matrices, and $\Delta \underline{x}$ is the vector of initial BPM errors (a linear orbit response is assumed). Corrector dynamics can be incorporated into a diagonal matrix $\mathbf{H}(s)$ containing transfer functions for each corrector. The dynamic error is then

$$\mathrm{E}(s) = \Delta \underline{x} - \mathbf{R}\,\mathbf{H}(s)\,(\mathbf{R}_{inv}\, \Delta \underline{\mathbf{x}}).$$

A simple algebraic transformation converts this to

$$\mathbf{E}(s) = \Delta \underline{\mathbf{x}} - \mathbf{P}(s)\,\mathbf{R}\,(\mathbf{R}_{inv}\, \Delta \underline{\mathbf{x}}).$$

If all correctors have the same dynamics, then both the $\mathbf{P}(s)$ and $\mathbf{H}(s)$ matrices are identity matrices multiplied by a scalar transfer function, and corrector dynamics appear directly on the residual orbit error. However, if the correctors have different dynamics, then $\mathbf{P}(s)$ is nondiagonal and there is *no simple relationship* between corrector dynamics and the residual orbit error. Viewed in SVD terms, if the correctors have different dynamics, then the SVD modes are no longer decoupled dynamically, even though they remain decoupled in a static sense.

At the APS, the correctors assigned to local feedback have a much slower response than those assigned to global feedback because of strong eddy current effects in the APS vacuum chamber (the global correctors have an Inconel vacuum chamber). The design of compensation filters for the slow correctors has proved to be very challenging, and consequently a spatial decoupling algorithm may not be achievable at the bandwidths required for global feedback.

The alternative is to decouple the two systems in frequency space, with the local feedback system taking care of only slow effects, and the global system taking care of dynamics effects. It may in fact be appropriate to only use local feedback when user steering is requested [2], in which case the global system could be used for both dynamic and slow effects, but would only take care of dynamic effects when steering requests are being applied.

7 ACKNOWLEDGMENTS

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