PERFORMANCE OPTIMIZATION FOR THE LNLS FAST ORBIT FEEDBACK

D. O. Tavares*, S. R. Marques, Brazilian Synchrotron Light Laboratory, Campinas, Brazil

Abstract

The Brazilian Synchrotron Light Laboratory (LNLS) is currently commissioning a Fast Orbit Feedback System (FOFB) for its 1.37 GeV UVX Storage Ring. This paper briefly reviews the evolution of FOFB systems and presents the optimization work which is planned for the LNLS ring using the new hardware capabilities. Well-known strategies such as singular values conditioning for correction matrix, dynamic control by means of PI and IMC controllers as well as the EVC method are discussed. The problem of actuator limitations (saturation and slew rate) is also investigated, providing a new front line for improving beam stability through orbit feedback.

INTRODUCTION

Fast Orbit Feedback (FOFB) systems have been in use in particle accelerators, since the early years of the 1990's decade. The goal of such systems is to mitigate fast orbit disturbances mainly due to mechanical vibration of lattice magnets, power supply (PS) ripple, booster cycles during top-up injection and insertion device gap-phase reconfiguration. They can replace or operate in combination with Slow Orbit Feedback (SOFB) and RF frequency correction systems to correct or attenuate slow disturbances such as magnetic field errors, thermal drifts and ground motion. The present systems can provide sub-micron global stability for the electron beam position integrated from 0 to around 250 Hz [1].

After a brief review of FOFB main topics, this paper will present the optimization approach which is planned for the LNLS Fast Orbit Feedback.

REVIEW OF FOFB SYSTEMS

The SVD Algorithm

The so-called Singular Value Decomposition (SVD) is today a *de facto* standard algorithm for orbit correction in accelerators, mainly due to its numerical robustness, ability to minimize the RMS closed orbit distortion (COD) or corrector strengths, and selecting the most effective correction modes in an insightful mathematical framework. It has gradually replaced the MICADO and harmonic algorithms with no prejudice to the orbit correction performance [2].

The well-known formulation is stated as follows:

$$R = USV^T \tag{1}$$

where R is the $m \times n$ beam response matrix (steady-state response), U is an $m \times m$ orthonormal basis matrix which rotates the input beam position vector into a new space (named mode space), V is an $n \times n$ orthonormal basis which transforms the corrector strengths vector from mode space to the actual corrector strength vector (or kick vector) and S is a $m \times n$ rectangular diagonal matrix containing the singular values of R.

A pseudo-inverse matrix of R which is normally used as beam correction matrix can be obtained by:

$$C = VS_{inv}U^T \tag{2}$$

where S_{inv} is a $n \times m$ rectangular diagonal matrix containing the reciprocals of the singular values of R.

Singular Values Filtering

The most basic treatment which can be done with the singular values of the response matrix is to identify those with very small magnitude. They correspond to the modes which will demand large excursions of corrector strengths to provide little contribution on the beam steering. A rule of the thumb is to keep the condition number, which is the ratio between the largest and the smallest singular values, below 100. This can be done by applying some regularization method and/or by eliminating the values below a chosen threshold. The Tikhonov regularization method has been used for this purpose [2], although other regularization methods could be used as well.

Local vs. Global Correction

A major concern with the first orbit feedback systems was how to deal simultaneously with global and local correction loops. While a slow orbit correction loop provided DC correction around the whole ring, fast orbit feedback loops applied local corrections by means of closed-bumps, aiming on stabilizing beam angle and position at selected source points. Although this was somewhat possible in the beginning, the addition of several local loops with independently reconfigurable insertion devices controlled by beamline users led to important bump leakages which compromised the global orbit stability.

One very elegant solution to this issue has been proposed in [3], the Eigenvector with Constraints (EVC) method. Using the Lagrange multipliers method, one can set constraints of zero position error for specific points in the ring whilst minimizing the least square error of the remaining BPMs. This approach solves the problem of uniting global and local orbit correction within the same correction scheme with a relatively simple formulation, summarized herein. First let us consider the matrix A

*daniel.tavares@lnls.br

and its decomposition in eigenvectors (V) and eigenvalues (λ):

$$A = R^T R \tag{3}$$

$$A = V \lambda V^T \tag{4}$$

It can be shown that the eigenvalues λ of the symmetrical matrix A are the square of the singular values of R, so that the above mentioned filtering of singular values can be made equivalently to the square root of the eigenvalues of A.

In this context, a *l x m* matrix Z is defined to select the *l* BPMs where zero error is desired. The i-th row and j-th column of Z is equal to 1 for indicating that the constraint i is set to the j-th BPM reading. The other elements of Z are zero.

The auxiliary matrices B and D are defined as:

$$B = (ZR)^T \tag{5}$$

$$D = \tilde{A}^{-1} B \left(B^T \tilde{A}^{-1} B \right)^{-1} \tag{6}$$

where $\tilde{A}^{-1}$ is the inverse of A obtained with the filtered reciprocals of the eigenvalues of λ.

Finally the beam correction matrix C is obtained, with filtered singular values and zero error constraints for a set of BPMs, by calculating the following expression:

$$C = DZ - (DB^T - I_n)\tilde{A}^{-1} R^T \tag{7}$$

where I_n is the *n x n* identity matrix.

Dynamic Control in Mode Space

Most of the FOFB systems operating today use a PI controller in each power supply setpoint to close the orbit correction loop. However, as described in [4] a tighter control, with improved performance and stability margins, could be achieved at Diamond using the Internal Model Control (IMC) and the Tikhonov regularization for the response matrix singular values. The architecture which was proposed in [5] included the orbit control in mode space, that is, a dynamic controller on each transformed corrector coordinate instead of the real corrector setpoints. However, due to the feedback processing hardware limitations, the traditional approach was applied and the treatment in mode space was done only via the singular values filtering.

OPTIMIZATION FOR LNLS FOFB

The optimization work which is planned for the LNLS UVX storage ring FOFB considers the use of PI controllers for each corrector power supply setpoint, singular values filtering for detuning the less effective/most demanding correction modes and the EVC method for guarantying zero error on critical BPMs. According to simulations, with the new control hardware capabilities [6] and the new fast corrector power supplies (currently in production phase), it might be possible to reach a maximum correction bandwidth around 50 Hz for the vertical plane (24 x 24 matrix).

The problem of actuator limitations (saturation and slew rate) is treated with a classical anti-windup loop, which prevents the closed-loop response from overshooting and even destabilizing when large current demands are sent to the power supplies. The dynamic controller structure is shown in Figure 1.

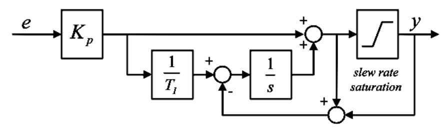

Figure 1: PI anti-windup structure.

PI Controller Tuning

Considering an open-loop response dominated by a first-order dynamics (the stainless steel vacuum chamber has 1.25 kHz bandwidth and can be neglected) due to the power supplies response (unitary gain $K_{PS} = 1$ and $\tau_{PS} = 0.5$ ms constant time) and a time delay ($\theta = 1$ ms) due to the data distribution over the acquisition and actuation networks, the simulated PI controller of Figure 1 was tuned with the following classical rules [7]:

$$T_i = \min(\tau_{PS}, 4 \cdot (\tau_{CL} + \theta)) \tag{8}$$

$$K_P = \frac{1}{K_{PS}} \frac{\tau_{PS}}{\tau_{CL} + \theta} \tag{9}$$

where τ_{CL} is the desired closed loop time response and was made $\tau_{CL} = 8\tau_{PS}$ to avoid great disturbance amplification above the feedback bandwidth. The maximum amplification is then limited to 1.5 dB at 150 Hz. The controller update rate is $T_S = 0.5$ ms. The actuator maximum slew rate is ± 0.2 A/ms and its amplitude saturation is ±10 A.

Directionality and MIMO System Bandwidth

Since global orbit feedback systems are essentially multiple-input-multiple-output (MIMO) systems, it is of crucial importance to take in account the "direction" of the disturbances (thinking in the beam position readings as vector coordinates) when analysing the closed-loop performance. Different disturbance directions lead to different system bandwidths, so that we must consider a bandwidth region for the system instead of a single bandwidth frequency [7].

In this regard, the approach here is to reduce the close-loop bandwidth for the high-order mode directions. Generally speaking, it makes the FOFB slower for the “difficult-to-correct disturbance directions” so that minimum steady state error (or zero error) is achieved in a longer time than for the “easy directions”. This was done by filtering the singular values as depicted in Figure 2.

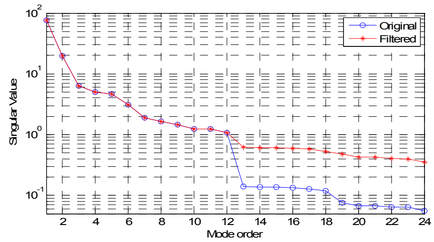

Figure 2: Vertical plane response matrix singular values.

Three levels of singular values can be observed, from modes 1-12, 13-18 and 19-24. The modes 13-18 were multiplied by a factor 20 and the modes 19-24 by a factor 40. With such change, the condition number decreased from 1387 to 219.

Figure 3 shows the disturbance rejection frequency response before and after filtering the singular values. It can be noted that the high-order modes were detuned in order to avoid unattainable power supply demands.

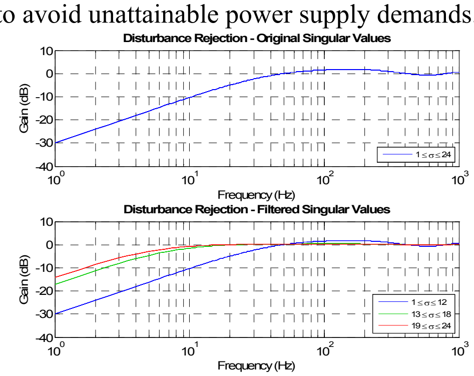

Figure 3: Sensitivity Function for Closed-Loop Response.

Figure 4 shows a step disturbance composed by a combination of the lowest-order and the highest-order mode disturbance direction (equal weights for each) with maximum position deviation of 100 μm.

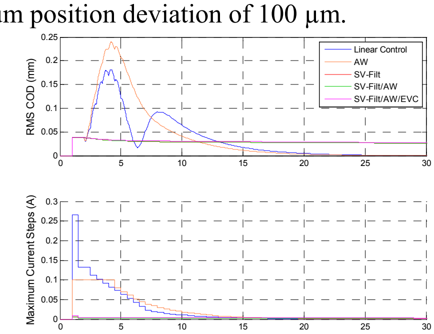

Figure 4: Step response with different closed-loop configurations: singular values filtering (SV-Filt), anti-windup strategy (AW) and zero error constraints for two BPMs (EVC).

When no singular value is applied, there is a great amplification of the disturbance due to actuators limitation. With the regularized singular values, the low-order mode is quickly vanished (<10 ms) while the high-order mode takes much longer time (~ 1s) to be corrected.

CONCLUSION

An overview of fast orbit feedback systems was given. Some of the present challenges for FOFB systems were identified: the dynamic control in mode space and the inclusion of actuator saturation and slew rate nonlinearities in the feedback control design. An initial strategy for optimizing the feedback loop is tried and the results show that the singular values filtering and anti-windup scheme are essential to obtain increased performance in closed-loop. The EVC method has proven to not significantly degrade the global COD while guarantying zero error for a small set of BPMs. For the LNLS UVX storage ring vertical plane, the simulations show that an effective correction bandwidth around 50 Hz for the low-order modes with maximum amplitude of 100 μm might be achieved. For the high-order modes, the corrections can be done with a much smaller bandwidth for guarantying no steady state error whilst not demanding unrealistic current setpoints to the power supplies. The optimization procedure will be applied in a more systematic way in order to achieve greater performance for the high-order modes.

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