FAST ORBIT RESPONSE MATRIX MEASUREMENTS AT ALBA

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Abstract

At ALBA the standard orbit response matrix measurement with a DC corrector magnet modulation is being upgraded with an AC excitation of the correctors combined with the synchronized BPM acquisition data rate at 10 kHz. Several types of excitation waveforms (sinusoidal vs square types) and frequencies have been tested and compared to optimize the measurement precision and repeatability. The data acquisition time of the ALBA response matrix (88 horizontal and 88 vertical correctors) with the new AC method takes 1 minute to complete instead of 7 minutes of the standard technique.

INTRODUCTION

The ORM measurement, along with the measured dispersion function and the beam position monitor (BPM) noise data, provides the input for the machine optics modeling and correction that are performed with the LOCO code [1,2].

The standard ORM is measured by varying one corrector magnet (CM) after the other with a bipolar DC current change, and acquiring the signal of the 120 BPM in the slow-acquisition (10 Hz) mode. Recording the orbit for each CM setting requires some extra pauses to ensure that the CM current change has been applied and that all the 120 BPM readings correspond to the same CM setting. For the ALBA storage ring there are 2×88 corrector magnets to cycle through, meaning the data acquisition takes around 7 minutes to complete.

In order to speed up the ORM measurement, we have decided to follow the method developed at Diamond [3,4], and which we call Fast Response Matrix (FRM) measurement. This technique is based on the synchronized fast-acquisition (FA) at 10 kHz data rate of the 120 BPM signals and the parallelization of the CM excitation using waveforms of different frequencies. This paper compares two different types of CM waveforms:

- Multiple Cycle Sinusoidal Waveforms (MCSW), denoted by the symbol $\sim$.
- Single Cycle Square Waveforms (SCSW), denoted by the symbol $\sqcap\!\sqcup$.

SCSW is a faster version of the standard DC measurement while MCSW can be parallelized using different frequencies. We present how the crosstalk between nearby frequencies can be taken into account. The first results using MCSW are shown, and the potential improvements of using SCSW are exposed. Finally, we also show how the precision of this method allows different non-linear beam dynamics studies.

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CORRECTOR WAVEFORMS

Deciding which type of waveforms leads to a more precise ORM measurement is a complicated task. Several barely quantitative points should be taken into account:

- Several cycles are needed to avoid hysteresis effects in the CM. In this case, parallelization using SCSW speeds up the process.
- At ALBA, the SCSW cannot be triggered via the timing system but using software triggers. This adds extra time delays to record the resulting orbit distortion. The effect is reduced when the triggers are parallelized as with MCSW.
- The BPM data noise has a non uniform spectrum, it is higher for frequencies below 13 Hz and in the 30-80 Hz range. This favors MCSW as in that case the frequencies can be chosen accordingly.

Following these considerations, we have implemented a MCSW FRM. However, as it will be shown here, a SCSW version implies potential precision improvements and full comparison of the two modes is still under process.

We next calculate the expected error bars which stem from each waveform type. Let $\sigma_{n,j}$ with $0 \le n < N$ be a set of normally distributed N reading errors of the j^{th} BPM with a standard deviation σ_j. Exciting N_c CM with MCSW of different frequencies of a given amplitude $\Delta I_\sim$, the N_c orbit response columns can be measured simultaneously. For a normal distribution and for a large number of samples N the precision of the amplitude measurements $\sigma_{j,k,\sim}$ of the k^{th} corrector with a normalized frequency ν_k (normalized by the 10 kHz rate) can be written roughly as:

$$\sigma_{j,k,\sim} = \frac{\sqrt{2}\sigma_j}{\sqrt{N}\Delta I_\sim}. \tag{1}$$

In the case of SCSW, the measurement should be not parallel but in series. To properly compare the result with the previous calculation, we take N/N_c measurements for each corrector. In this case the measurement precision $\sigma_{j,k,\sqcap\sqcup}$ of the k^{th} corrector can be written as:

$$\sigma_{j,k,\sqcap\sqcup} = \sum_{n=0}^{N/N_c-1} \frac{N_c \sigma_{n,j}}{N \Delta I_{\sqcap\sqcup}}. \tag{2}$$

If N/N_c is a large number, for a normal error distribution we obtain:

$$\sigma_{j,k,\sqcap\sqcup} = \frac{\sqrt{N_c}\sigma_j}{\sqrt{N}\Delta I_{\sqcap\sqcup}}. \tag{3}$$

For a proper comparison, in the case of the MCSW the waveform amplitude $\Delta I_\sim$ should give the same maximum beam distortion that the single SCSW amplitude $\Delta I_{\sqcap\sqcup}$, and

ISBN 978-3-95450-182-3

so $\Delta I_{\sqcap\sqcup} = N_c \Delta I_{\sim}$. This allows to establish the following relation between the precision of both methods:

$$\sigma_{j,k,\sqcap\sqcup} = \frac{\sigma_{j,k,\sim}}{\sqrt{2N_c}}. \tag{4}$$

This result indicates that the higher the parallelization, the worse the MCSW based method performs in comparison with the SCSW based method. Even if the MCSW are not parallelized, the SCSW based method should be a factor $\sqrt{2}$ better because it produces a higher signal to noise ratio during the waveform period.

ORBIT RESPONSE FROM PARALLEL MCSW

In the MCSW case, the measurement of the orbit response to a group of N_c CM is parallelized using a set of normalized frequencies $\nu_1, ..., \nu_{N_c}$. As a result, the BPM readings contain a linear superposition of the response to each CM waveform. Neglecting errors and non-linear behaviors, the j^{th} BPM readings $x_{j,n}$ in either plane can be expressed as:

$$x_{j,n} = \sum_{l=1}^{N_c} M_{j,l} \cos\left(2\pi n \nu_l + \phi_{j,l}\right), \tag{5}$$

where $M_{j,l}$ and $\phi_{j,l}$ determine the element $ORM_{j,l}$ of the corresponding plane, since $ORM_{j,l} = M_{j,l} \cdot \mathrm{sign}\left(\phi_{\mathrm{j,l}}\right)$.

The projection $\hat{c}_{j,k}$ at the k^{th} excitation frequency is used to obtain the values from the j^{th} BPM readings:

$$\hat{c}_{j,k} = \sum_{n=0}^{N-1} x_{j,n} e^{-2\pi i n \nu_k}. \tag{6}$$

For every BPM j, Eq. 6 establishes a set $2N_c$ equations that correlate the real ($\Re$) and imaginary ($\Im$) part of the projections $\hat{c}_{j,k} = \hat{a}_{j,k} + i\hat{b}_{j,k}$ with the real and imaginary part of the single signal values $M_{j,l} e^{i\phi_{j,l}} = a_{j,k} + ib_{j,k}$. After some algebra, Eq. 6 can be rewritten as:

$$\begin{aligned} \hat{a}_{j,k} &= \sum_{l=1}^{N_c} \left[\Re\left(\xi^+_{kl} + \xi^-_{kl}\right) a_{j,l} - \Im\left(\xi^-_{kl} - \xi^+_{kl}\right) b_{j,l}\right], \\ \hat{b}_{j,k} &= \sum_{l=1}^{N_c} \left[\Im\left(\xi^+_{kl} + \xi^-_{kl}\right) a_{j,l} + \Re\left(\xi^-_{kl} - \xi^+_{kl}\right) b_{j,l}\right], \end{aligned} \tag{7}$$

where ξ^+_{kl} and ξ^-_{kl} are defined as follows:

$$\xi^{\pm}_{kl} = \frac{1}{2} \frac{1 - e^{-2\pi i N(\nu_k \pm \nu_l)}}{1 - e^{-2\pi i(\nu_k \pm \nu_l)}}. \tag{8}$$

The linear system described by Eq. 7 can be inverted for a set of different frequencies. This allows to measure multiple CM responses even if their frequencies are close to each other.

MCSW MEASUREMENT RESULTS

Given the limitation on the maximum rate of the CM power supply, and the fact that the BPM noise spectrum has a minimum at the 13 to 18 Hz range, the FRM has been measured using frequencies in that range.

The ALBA storage ring consists of 16 sectors, each one with 5 or 6 horizontal and vertical CM. We have chosen to parallelize all the 10 or 12 CM of each sector. To compare the performance of each case, the FRM is measured 5 times and the ratio between the standard deviation (STD) among the 5 cases and the ORM STD was used. The four ORM are compared: horizontal BPM vs horizontal CM (R_{xx}), horizontal BPM vs vertical CM (R_{xy}), vertical BPM vs horizontal CM (R_{yx}) and vertical BPM vs vertical CM (R_{yy}).

Figure 1 shows the relative STD as a function of the acquisition time per sector. The improvement with respect to the slow orbit acquisition method ranges from a factor 3 to 30 depending on the plane and the acquisition time. The measurement time ranges from 32 (2 seconds per sector) to 124 seconds (8 seconds per sector), consequently the FRM is in any case significantly faster than the standard ORM measurement (7 minutes). Using an average case (6 seconds per sector) a complete LOCO measurement takes 2.3 minutes instead of 9.4 minutes in the standard ORM case.

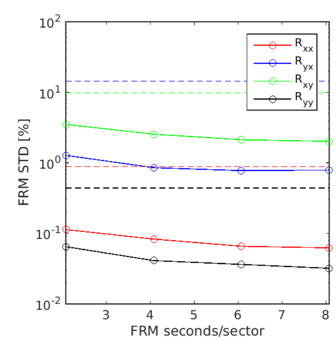

Figure 1: Relative STD among 5 FRM cases for each of the 4 BPM and CM planes plotted against the time of acquisition per sector. The standard ORM relative STD is plotted in dashed lines for the 4 planes but using in the same colors.

NON LINEAR DYNAMICS

The FRM technique allows a much more precise ORM measurement and hence makes it possible to measure higher order ORM terms. An example of that are the energy derivative of the response matrix $\frac{\partial ORM}{\partial \delta}$ and the non-linear response matrix ORM^2. Both quantities can be used to fit the non-linear dynamics.

The measure of $\frac{\partial ORM}{\partial \delta}$ consists in acquiring a few FRM at different RF frequencies around the central RF frequency. On the other hand, to measure ORM^2 we can take the BPM FA signal amplitude at harmonics of the CM frequencies. These harmonics are present in the beam motion through

ISBN 978-3-95450-182-3

the non-linear response to the magnetic fields, mainly the sextupolar fields:

$$B_y = m\left(x^2 - y^2\right), \tag{9a}$$

$$B_x = 2mxy, \tag{9b}$$

where m represents the normalized sextupole field strength. When CM of both planes are excited with waveforms of frequencies f_x and f_y respectively, the term in Eq. 9a introduces the frequencies $2f_x$ and $2f_y$ in the horizontal plane motion. Similarly, the term in Eq. 9b introduces the frequencies $f_x + f_y$ and $f_x - f_y$ in the vertical plane motion. Frequencies corresponding to the same CM plane are alternated.

NON LINEAR MEASUREMENTS

Energy Derivative of the Linear Response Matrix

Figure 2 (left) shows how a particular ORM element changes with the beam energy (by changing the RF). This type of measurements were not possible with the standard ORM measurement due to the high noise of data. With the FRM, the first and also the second order (not shown) derivatives of the ORM with respect to energy can be measured for all CM and BPM as shown in Fig. 2 (right).

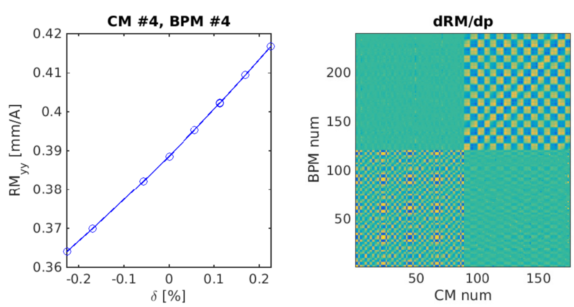

Figure 2: Measurements of the ORM for a particular element as a function of the beam energy δ (**left**) and $\frac{\partial ORM}{\partial \delta}$ for the whole set of BPM and CM (**right**).

Non Linear Response Matrix

For a proper ORM^2 measurement, the parallelization is limited by the need of producing large beam oscillation amplitudes to trigger the non-linear effects of the magnetic fields.

Figure 3 (top) shows the discrete spectrum of the beam motion when a vertical CM is excited with a 1.333 Hz waveform. The lower plot shows the measured 2.666 Hz spectral line amplitude compared with simulation. In future tests, this can be repeated with all the vertical and horizontal CM to collect more information about the non-linear dynamics.

CONCLUSIONS AND OUTLOOK

A FRM measurement technique is being implemented at ALBA. This system is able to excite in parallel several CM with sinusoidal waveforms at different frequencies and

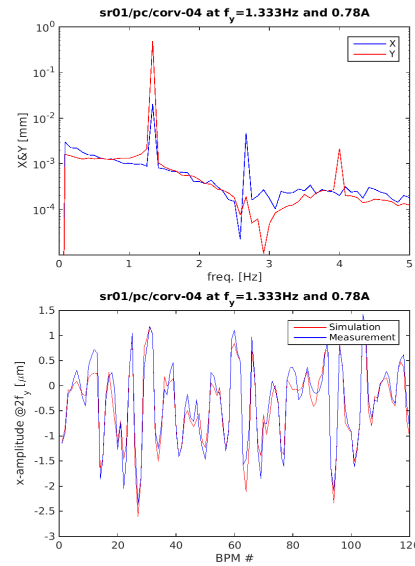

Figure 3: (**top**) Measured beam motion discrete spectrum in the horizontal (blue line) and vertical (red line) planes after exciting a single vertical corrector with a waveform with fre-quency f_y = 1.333 Hz and a amplitude of 0.78 A. Note that a clear second harmonic 2 f_y appears in the horizontal plane.(**bottom**) Amplitude in the horizontal plane of the second harmonic of the vertical plane frequency f_y for all BPM along the ring. Simulations (red line) and measurements (blue line) are compared.

acquiring synchronously the signal of the 120 BPM at a 10 kHz rate. Compared with the standard DC method to measure the ORM, the data acquisition is reduced by about a factor 7 using waveforms with frequencies between 13 and 18 Hz and parallelizing the CM excitation sector by sector. The ORM STD is reduced by a factor between 3 to 30 depending on the plane and the acquisition time. This im-provement allows several non-linear beam dynamics studies based on the higher order response matrix terms, such as the energy derivative of the response matrix or the non-linear response matrix. A more complete comparison using square waveforms is under test, which could potentially reduce the STD.

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ISBN 978-3-95450-182-3