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COMPARISON BETWEEN DIGITAL FILTERS AND SINGULAR VALUE DECOMPOSITION TO REDUCE NOISE IN LHC ORBITS USED FOR ACTION AND PHASE JUMP ANALYSIS*

Alba-Carolina Garcia-Bonilla, Javier Fernando Cardona†, UNAL, Bogota, Colombia

Abstract

One of the initial difficulties to apply the Action and Phase Jump (APJ) analysis to LHC orbits was the high level of noise present in the BPM measurements. On the other hand, the unprecedented number of turns for LHC allows us to use all sort of filters. In this paper, we evaluate the effectiveness of digital filters like the band-pass filter and compare them with a filter based on Singular Value Decomposition, when magnetic error estimations are made using a recent version of the APJ method. First, mainly results on simulated orbits with noise are presented, and then, plots and results are shown for the filters effect on experimental data. The analysis indicates that a combination of filters leads to measurements with the least uncertainty.

INTRODUCTION

The Large Hadron Collider (LHC) is a machine designed to have two beams of particles, which encounter each other in four points along a ring of 26.7 Km. The LHC system is capable of running and measuring all 2808 bunches of the beam. For this task, the Beam Position Monitors (BPMs) have a much wider bandwidth than previous colliders [1].

A requirement for optical measurements is that each beam uses only one single bunch for security reasons. Therefore, with the wide bandwidth of the BPMs, the measurements have a considerable amount of noise when compared to others accelerators.

On the other hand, the unprecedented number of turns available per measurement in the LHC allows us to use all sort of filters to drastically reduce such noise, some of which have been already presented [2–5].

In this paper, we evaluate the effectiveness of digital filters like the band-pass filter and compare them with a filter based on Singular Value Decomposition, which is currently used in the LHC. First, the results of the filters and its combinations on simulated orbits are presented, and then, results from experimental data with the same filters are shown.

The technique used to measure the magnetic errors is the Action and Phase Jump Analysis (APJ), in particular, the new formulation, explained in [6].

DIFFERENT WAYS TO REDUCE NOISE

During this investigation, initially, we studied the effectiveness of the dual band-pass filter (described in [2]) in reducing the noise. This, by using the signal-to-noise (STN) ratio quantity, which is independent of the technique used to obtain the magnetic errors. Trials to separate the noise from the signal were performed, like taking the difference of the orbit with and without noise after using the filter. Generally, the filters change the output signal amplitude, so we applied the filter for both, the signal before adding noise and the signal with noise to have a comparison.

It was found that generally the noise is reduced more faster than the amplitude, as the bandwidth ($\Delta\omega$) of the dual pass-band filter decreases. Sometimes there was an optimum $\Delta\omega$ which was different depending on the magnetic error[1].

Also, we developed studies for the sensitivity of the band-pass filter with frequency. Initially, fictitious sinusoidal signals with fraction frequencies between 0.0 and 0.5 (like in the real accelerator) were used, and it is found that the filter is effective at any of these frequencies. Actually, the filter changes a bit the Fourier frequency at the points closer to the central band but this is not a problem to obtain the magnetic errors as proposed. Later this was corroborate with some Mad-X simulations for the LHC.

Therefore, the most convenient way to apply the band-pass filter is to do a simulation curve to establish a range for the optimal band-width according to the experimental conditions. The type of curves proposed are discussed later.

To reduce noise on turn-by-turn orbits in the LHC, the filters that have been used are: a filter based on the average of many orbits (*Prom*) [3], a dual band-pass filter (*Band*) [2], and a filter based on singular value decomposition (*Svd*) [4], Combinations of these filters can be built and the following cases are analyzed:

1. Prom
2. Band
3. Svd
4. BandProm
5. SvdProm
6. BandSvdProm
7. SvdBandProm

Composed names like "BandProm" means that the band-pass filter is applied and then the "Prom" filter.

RESULTS ON SIMULATIONS

The comparison between the studied filters are based on the exactness and precision of the measurements obtained from LHC orbits using the APJ method.

Although it is not possible to compare a simulation with the experimental data because not all what is happening in reality can be modeled in the simulation, a simulation close

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† jfcardona@unal.edu.co

[1] During these studies, the most effective bandwidth changes according with the type of error, the transverse plane used, and even more with the amount of noise

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Table 1: Results for the Normal Errors using Simulated Orbits

Simulation	$\Delta\omega$ 2π [rad]	**B1(Q1)** 10^{-6} [m^{-2}]	σ**B1(Q1)** 10^{-7} [m^{-2}]	$\Delta\omega$ 2π [rad]	**B1(Q2)** 10^{-5} [m^{-2}]	σ **B1(Q2)** 10^{-8} [m^{-2}]
No Filter	—	-10.8	24.0	—	-1.27	154
Prom	—	-10.0	1.91	—	-1.30	12.8
SvdProm	—	-9.97	1.46	—	-1.30	11.1
	0.05	-9.92	1.03	0.04	-1.31	8.54
BandProm	0.04	-9.96	1.16	0.04	"	"
	0.125	-9.86	0.822	0.065	-1.30	5.76
BandSvdProm	0.01	-9.94	1.14	0.04	-1.31	8.26
	0.125	-9.86	1.03	0.0003	-1.30	6.76
SvdBandProm	0.05	-9.94	1.13	0.0005	-1.30	7.90

to the set-up used for the data taken in LHC on April 13th, 2010, was done.

This simulation is done for the LHC B1 V6.5.seq, low β^* using MAD-x, for 2000 turns and with two normal quadrupole errors, and one skew error in the quadrupoles at IR5. The quadrupoles are named **B1(Q1)**, **B1(Q2)** and **A1** respectively. See [6] for details.

The simulated orbit is then modified by the addition of noise with normal distribution. Plots for each magnetic error recovered against the band-pass filter bandwidth ($\Delta\omega$) are constructed, and the uncertainty σ is obtained as the standard deviation. 20 orbits for each case are generated.

For each magnetic error, the best filter (smallest σ) found is always a combination of filters. When $\Delta\omega < 0.002$ all the combinations of filters turn out to be effective to reduce σ. On the other hand, for each magnetic error the same filter has a different behavior, for example, "BandProm" for **B1(Q1)** has a lesser dispersion compare to the same filter and its results for **B1(Q2)**.

Table 2: Results for the Skew Error using Simulated Orbits

Simulation	$\Delta\omega$ 2π [rad]	**A1** 10^{-4} [m^{-2}]	σ **A1** 10^{-6} [m^{-2}]
No Filter	—	2.97	72.5
Prom	—	3.01	7.65
SvdProm	—	3.00	4.55
	0.045	3.01	3.31
BandProm	0.04	3.02	4.12
	0.075	3.02	3.27
BandSvdProm	0.045	3.01	3.95
	0.075	3.02	3.15
SvdBandProm	0.045	3.02	3.86

Tables 1 and 2 show the results with no filter, the individual filters and the best three combinations for each magnetic error. In some cases, there is not a filter that stands out with respect to the others; for the **A1** case, the two first cases are closer to each other and they are also close to the following two options. In the tables, the filters with two rows corresponds to the $\Delta\omega$ that leads to the smallest σ, and the most common $\Delta\omega$ from the five best filters using both formulations of the APJ method, and it is included to have an idea of the margin of variations of these values.

The filter "Svd" is implemented with software[2] developed at CERN by the OMC team. The results show that "Svd" has a considerable larger σ than the best filter or "Prom", and this happens for every value and position of the magnetic error.

Results also show that σ for "Prom" have approximately the same value as σ for the best filter for all the magnetic errors when $\Delta\omega > 0.2$. For the best filter, which is different for each magnetic error, σ (the error bars) does not have a clear mathematical function dependence on the bandwidth.

RESULTS USING LHC DATA

Performing an analysis using the same filters and similar as above, magnetic errors are measured from LHC data. The analyzed orbits are the data taken in LHC on April 13th, 2010 at 12:54:09, 12:56:24 and 12:59:18. This corresponds to 3 orbits from which 6 values are obtained, two values from each orbit.

Tables 3 and 4 show the results from the experimental data. More dispersion is observed compare to the simulations.

Figure 1 presents the proposed type of curves to obtain the optimal bandwidth, for the **B1(Q1)** case. According to the tables, the best filter changes for each magnetic error so the proposed curves should include these changes. The optimal bandwidth is identified from the plot of σ against $\Delta\omega$, plotted at the right of the Figure 1, the procedure is to find the points closer to 0 in the ordinate, and with the help of the plot for magnetic error recovered, establish if a range around that points has the same tendency.

In the left plot of Figure 1, the magnetic error measurement is plotted against $\Delta\omega$; the results of the "Band" filter are out because their error bars are twice or more than the "Svd" bars for $\omega > 0.01$, although they get much smaller as the bandwidth is decreased from that point. The error bars

[2] Initially the configuration used has 100 singular values, then in concordance with [4], we use 8 and 4 singular values. The least uncertainty value is with 4, for the two (B_1) cases, while for three magnetic errors (A_1, $B_{1,I}$, $B_{1,II}$), the least uncertainty is reached with 8 singular values.

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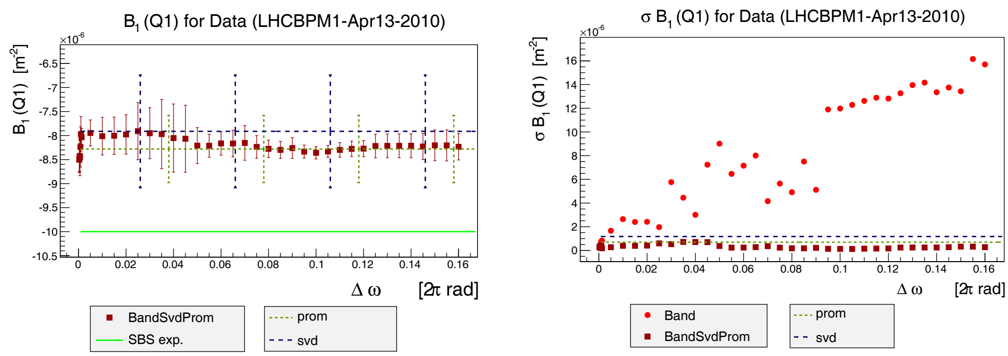

Figure 1: Comparison between filters, for the **B1(Q1)** measurement using LHC experimental data. The plot at the left shows the recovered value against the bandwidth, and at the right, its uncertainty. The reference value (solid green line) is the measurement given by the Segment-by-Segment technique [3].

Table 3: Results for Filters Applied on LHC data

Data LHC_B1-Apr13/10	$\Delta\omega$ 2π [rad]	**B1(Q1)** 10^{-6} [m^{-2}]	σ **B1(Q1)** 10^{-7} [m^{-2}]	$\Delta\omega$ 2π [rad]	**B1(Q2)** 10^{-5} [m^{-2}]	σ **B1(Q2)** 10^{-8} [m^{-2}]
No Filter	—	-21.0	133	—	-0.59	1050
Prom	—	-8.28	6.98	—	-1.54	92.2
SvdProm	—	-8.05	4.34	—	-1.54	38.4
BandProm	0.0013	-8.11	2.49	0.02	-1.54	4.86
BandSvdProm	0.1050	-8.33	1.24	0.03	-1.54	5.97
SvdBandProm	0.145	-8.03	2.96	0.015	-1.56	32.6

are given by σ and for the filters independent of $\Delta\omega$ their bars are at four equidistant points. The solid green line is the reference value which is the measured value obtained by the OMC team using the SBS technique. Three cases have to be identified when analyzing experimental data as above. If the bandwidth is too wide less noise is filtered but all the resonance lines are taking into account, on the contrary, if the bandwidth is too sharp the betatron frequency might be out of the band of the filter and the error cannot be detected. Intermediate states are when some resonances are included.

Table 4: Summary of Results for **A1** using LHC Data

Data LHC_B1 Apr13/10	$\Delta\omega$ 2π [rad]	**A1** 10^{-4} [m^{-2}]	σ**A1** 10^{-6} [m^{-2}]
No Filter	—	6.03	63.00
Prom	—	3.06	3.76
SvdProm	—	2.80	4.04
BandProm	0.1	3.19	1.34
BansSvdProm	0.01	3.02	2.03
SvdBandProm	0.015	2.81	3.53

In all cases, the filter "Prom" has the advantage of being significantly faster than the other filters but the results show that its uncertainty can be as twice as big as the best combination of filters studied in this paper.

CONCLUSION

Digital filters applied on noisy orbits to obtain magnetic errors do not have absolute results. Using the APJ analysis a combination of filters leads to the measurement with the least uncertainty. There are two options: to use the pass-band filter (*Band*), then the filter based on singular values decomposition (*Svd*) and finally do the average (*Prom*); or to use first the *Svd* then *Band* and finally *Prom*. In this way the uncertainty decreases about 50% compare to the individual use of filters. Also, it is observed that with *Prom* there is always a lesser uncertainty than when using only *Svd*.

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