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AN ALTERNATIVE PROCESSING ALGORITHM FOR THE TUNE MEASUREMENT SYSTEM IN THE LHC

L. Grech*, G. Valentino
Department of Communications and Computer Engineering, University of Malta, Msida, Malta
D. Alves, M. Gasior, S. Jackson, R. Jones, T. Levens, J. Wenninger
Beams Department, CERN, Geneva, Switzerland

Abstract

The betatron tune in the Large Hadron Collider (LHC) is measured using a Base-Band-Tune (BBQ) system. Processing of these BBQ signals is often perturbed by 50 Hz noise harmonics present in the beam. This causes the tune measurement algorithm, currently based on peak detection, to provide tune estimates during the acceleration cycle with values that clearly oscillate between neighbouring harmonics. The LHC tune feedback cannot be used to its full extent in these conditions as it relies on stable and reliable tune estimates. In this work we present two alternative tune measurement algorithms, designed to mitigate this problem by ignoring small frequency bands around the 50 Hz harmonics and estimating the tune from spectra with gaps. One is based on Gaussian Processes and the other is based on a weighted moving average. We compare the tune estimates of the new and present algorithms and put forward a proposal that can be implemented during the renovation of the BBQ system for the next physics run of the LHC.

INTRODUCTION

The tune (Q) of a circular accelerator is defined as the number of betatron oscillations per turn [1]. This is a critical parameter in the Large Hadron Collider (LHC) which has to be monitored and corrected in order to ensure stable operations [2] and adequate beam lifetime. The Base-Band Q (BBQ) system in the LHC is used to measure the tune. It essentially consists of an electromagnetic pickup followed by a diode-based detection and acquisition system [3]. The diode detectors pick-up a small modulation caused by betatron motion on the large beam intensity pulses and converts it to baseband, which for the LHC is in the audible frequency range. The BBQ system in the LHC is sensitive enough to not require that the beam is externally excited in order to measure the tune, picking-up the residual beam oscillations. This normally results in a frequency spectrum where the tune is the dominant peak [3, 4].

Since the start of the LHC, spectral components at harmonics of the 50 Hz mains frequency have been observed with several different diagnostic systems [5]. Studies have shown that these modulations are on the beam itself, although their source is unclear. These harmonics are clearly visible in the BBQ system, resulting in a frequency spectrum polluted with periodic lines every 50 Hz (Fig. 1). Since these harmonics are also present around the betatron tune, they are a potential source of error for the tune estimation algorithm. The current tune estimation algorithm applies a series of filters and averaging techniques which have been developed in order to mitigate the impact of the 50 Hz harmonics on the final measured value. However, it is not uncommon to have the estimated tunes oscillate between neighbouring 50 Hz harmonics. The fact that the tune estimate locks-in to a particular ~50 Hz harmonic is clearly not desirable. On top of that, having the tune jump from one line to another affects the tune feedback system, causing it to switch off as a protective measure against unstable behaviour.

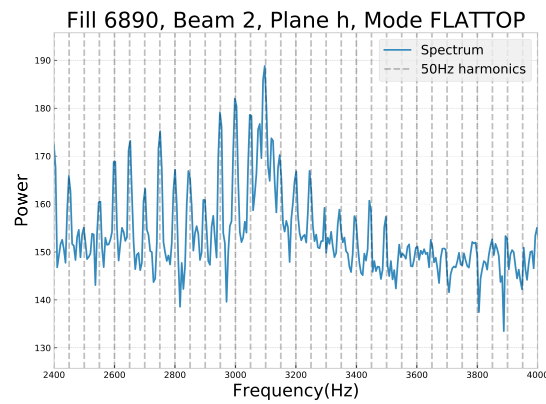

Figure 1: Example of 50 Hz harmonics present in the BBQ spectrum.

In this paper, we present a study on alternative approaches for the tune estimation algorithm. The common underlying idea is to mask-out the 50 Hz harmonics from the frequency spectrum of the BBQ signal. Following this, a polynomial fit, a weighted moving average and Gaussian Processes have been selected for comparison in terms of tune estimation performance.

We begin by describing the presently implemented tune estimation algorithm and then proceed to describe the proposed alternatives. We then perform a thorough comparison of all methods by simulating numerous plausible BBQ spectra for different tune values and widths. Finally we show two examples with comparisons between all three methods applied to recorded BBQ data and finish with concluding remarks.

* leander.grech@um.edu.mt

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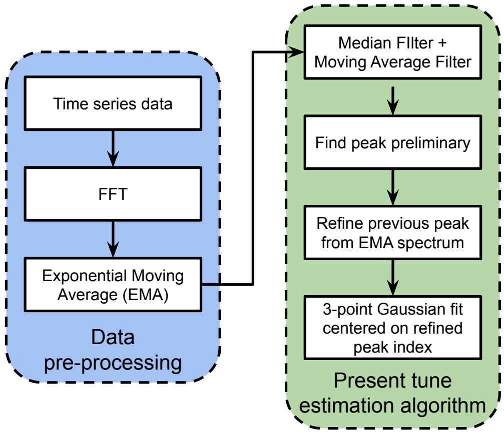

Figure 2: Present algorithm diagram.

PRESENT TUNE ESTIMATION ALGORITHM

The present tune measurement system is normally configured to provide a spectrum of 1024 frequency bins at a rate of 6.25 Hz. Since the original signal is sampled at the LHC revolution frequency of approximately 11 kHz, the spectral resolution is approximately 5.5 Hz. The set of sequential processing blocks which form the present tune estimation algorithm is depicted in Fig. 2. First, each calculated spectrum update is passed through a bank of independent exponential moving average filters, each of them working on a single frequency bin. This pre-processing stage is essentially used to reduce spectral noise. Median and average filters are subsequently applied to the spectrum to increase its smoothness and mitigate the effect of the 50 Hz harmonics. At this stage the frequency corresponding to the maximum value of the processed spectrum is taken. This frequency is subsequently refined by going back to the output of the bank of exponential moving averages and performing a Gaussian fit of the spectral region in its immediate vicinity.

ALTERNATIVE ALGORITHMS

With a spectral resolution of 5.5 Hz, changes of the mains frequency at the percent level hardly impact the centre and width of the spectral regions containing the 50 Hz harmonics. Therefore, the periodic regions with the observed 50 Hz harmonics remain fairly unchanged. These regions have a finite width mainly due to the effect of the jitter on the 50 Hz mains frequency coupled with the smoothing introduced by the spectral filter bank.

With this in mind, we have added an extra pre-processing stage immediately after the exponential moving average filter bank which removes the spectral points lying inside the affected regions. The reasoning behind this stage is that the information contained in this region is completely dominated by the presence of the 50 Hz harmonics peaks and can often mask the true tune peak. Furthermore, even if the tune itself happens to be on top of a 50 Hz dominated region, and since the overall number of disregarded points will be less than a fourth of the total number of points, the spectral baseline can still be recovered. This leaves us with an overall smoothed-out spectrum which contains periodic gaps every 50 Hz.

The approach we propose is to employ algorithms capable of handling non-uniformly sampled signals (in this case, spectra with frequency gaps) for interpolation prior to retrieving the maximum of the spectral baseline, corresponding to the true tune value.

The first naive approach was to fit a polynomial over the spectrum with gaps, however it was observed that a 10^{th} order or higher polynomial is needed to obtain a close fit. This approach did not prove to be very reliable, especially at the extremities of the spectrum, where the quality of the fit is worst, resulting in poor estimates of the tune frequency.

We will now describe two more promising algorithms considered in this study.

Weighted Moving Average

The second algorithm which was attempted was a Weighted Moving Average (WMA). Here we consider a sliding window of size $2L+1$, where the weight of each component within the window depends on its distance from the center of the window. Therefore:

$$\hat{y}_i(L) = \frac{\sum_{j=-L}^{L} w(j,L) \times y_{i+j}}{\sum_{j=-L}^{L} w(j,L)}$$

where:

$$w(k,L) = \begin{cases} L-|k| & \text{, if } \exists\, y_{i+j} \\ 0 & \text{, if } \nexists\, y_{i+j} \end{cases} \tag{1}$$

Here the second case of Eq. (1) occurs at the edges of the spectrum and where a frequency bin has been removed to form a gap. When setting up the algorithm, one has to take care to make the sliding window greater than the size of the largest gap in the array to avoid that the averaging is performed within the gap.

Gaussian Processes

The third algorithm uses a Bayesian modelling approach with Gaussian Processes where, by using the available data points, a statistical model is built which includes all the uncertainty introduced in the data when the 50 Hz harmonics are removed from the dataset. Gaussian Processes can be thought of as a distribution of functions where, by drawing a sample from the distribution, one of the infinitely possible functions described by the Gaussian Process is obtained [6]. Such a sample function is drawn from a multi-variate normal distribution:

$$f(X) \sim \mathcal{N}(\mu = m(x), \Sigma = k(X,X)) \tag{2}$$

where $m(x)$ is usually assumed to be a zero vector and $k(X,X)$ is a positive definite covariance function. The aim would ultimately be to predict the output, y_2, of some input dataset, X_2. Given some previously observed data, (X_1, Y_1),

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a covariance matrix, Σ, can be built. Σ models the joint variability of the input variables via a prior function, also known as a kernel. One such kernel is the exponentiated quadratic kernel, or Radial Basis Function (RBF) kernel, which uses the squared Euclidean distance between points x_a and x_b as a measure of correlation between the points:

$$k(x_a, x_b) = e^{-\frac{1}{2\sigma^2}\|x_a - x_b\|^2} \tag{3}$$

Here σ is a free parameter controlling the smoothness of the resulting distribution. Under these conditions a new distribution can be derived, which takes in the observations from (X_1, Y_1) to make predictions over a new input dataset, X_2:

$$P(y_2 \mid y_1, X_1, X2) \sim \mathcal{N}(\mu_{2|1}, \Sigma_{2|1}) \tag{4}$$

where:

$$\mu_{2|1} = \left(\Sigma_{11}^{-1}\Sigma_{12}\right)^{\top} y_1$$
$$\Sigma_{2|1} = \Sigma_{22} - \left(\Sigma_{11}^{-1}\Sigma_{12}\right)^{\top} \Sigma_{12}$$
$$\Sigma_{ab} = k(X_a, X_b)$$

BENCHMARKING

When it comes to real experimental data, it is not possible to know the precise value of the tune. As a consequence, we decided to do the performance evaluation of these algorithms via multiple spectral simulations of second-order systems where we know the true value of the tune. The spectrum of a second-order system is given by:

$$G(\omega) = \frac{\omega_{\text{res}}^2}{\sqrt{(2\omega\omega_{\text{res}}\zeta)^2 + (\omega_{\text{res}}^2 - \omega^2)^2}} + \mathcal{N}(0, \sigma), \tag{5}$$

where the resonant frequency, i.e. the true tune value, is given by:

$$\omega_{\text{res}}^{\text{true}} = \sqrt{1 - 2\zeta^2}\,\omega_{\text{res}}. \tag{6}$$

Here ζ is a damping factor that controls the width of the resonance, and $\mathcal{N}(0, \sigma)$ an additive spectral noise term. Since the motion of a particle in a circular accelerator can be described by a Hill's equation we can assume that the frequency spectrum of the beam as seen by the BBQ system is approximated by that of second-order system.

A Monte Carlo approach was used to sample the resonant frequencies and the damping factors which were used to simulate the frequency spectrum of the beam. Moreover Gaussian noise, as well as 50 Hz harmonics were artificially introduced into the simulated spectrum. By using this approach, the reliability of these algorithms could be impartially assessed.

The resonant frequencies were sampled from a normal distribution with a mean of 3 kHz and a standard deviation of 200 Hz, while the damping factors were sampled from a uniform, logarithmic distribution of base 10 within the range $[10^{-4}, 10^{-1}]$ corresponding to different tune resonance widths. These ranges were chosen to mimic real

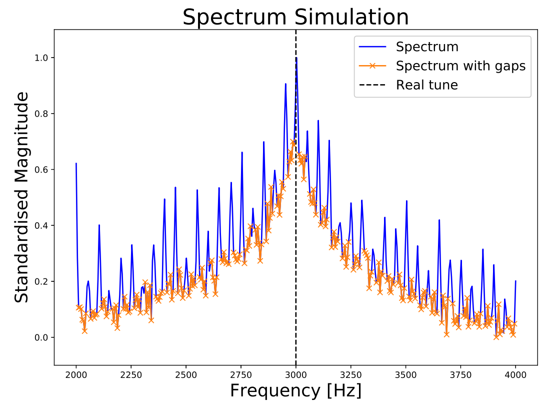

Figure 3: Example of a simulated spectrum with f_{rev} = 3 kHz and ζ = 0.01.

experimental observations. Figure 3 shows an example of a simulated spectrum having a resonant frequency of 3 kHz and ζ of 0.01. The simulated spectrum also has 50 Hz harmonics and Gaussian noise superimposed. On the same figure, the orange plot shows the resulting spectrum with gaps, after dropping all the data within a 10 Hz window around each harmonic.

For each simulated spectrum, all four algorithms were used to estimate the tune, and the statistics of the estimation error assessed in order to benchmark the different approaches. The Weighted Moving Average (WMA) was performed using three different window sizes (10, 30, 60), while the Gaussian Process (GP) was performed using three different length scales (25, 70, 130), where the length scale is associated with the σ free parameter as seen in Eq. (3). The polynomial fit was of degree 15 and the original algorithm (BQ) as presently implemented in the online system was faithfully re-implemented in order to be compared against the new algorithms.

RESULTS

Monte Carlo Simulation Results

An overview of the statistics of the tune estimation errors obtained from the Monte Carlo simulation can be seen in Fig. 4 and in Table 1. The first observation one can make is that there seems to be a similar systematic error in the BQ, WMA60 and GP130 algorithms. There is also a smaller systematic error in GP70 and WMA30. GP25 and WMA10 show a higher accuracy, in the sense that the mean of the errors is centred almost perfectly around 0, however they seem to lack the precision of BQ, GP70, GP130, WMA30 and WMA60. POLY15 shows a small systematic error, but a poor precision when compared to all the other methods.

Another important aspect that is shown in Table 1 is the worst case estimation error, directly related to the tails of the distribution. Overall, it seems that algorithms set up to achieve high accuracy have a poorer precision. This suggests that there is a trade-off of between precision and accuracy that can be controlled by the parameters of each algorithm.

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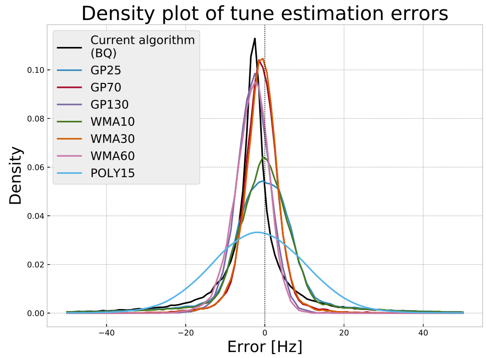

Figure 4: Density plot of the errors from the Monte Carlo simulation. In the legend, WMA30 refers to WMA with a window of size 30, GP130 refers to GP with a length scale of 130, and so on.

Table 1: Tune Estimation Error Statistics

Algorithm	μ[Hz]	σ[Hz]	Max abs err[Hz]
BQ	-3.0	12.8	114.7
GP25	-0.2	12.4	119.1
GP70	-1.1	5.2	43.8
GP130	-3.0	4.4	22.3
WMA10	-0.2	11.6	119.0
WMA30	-1.0	4.9	98.4
WMA60	-3.4	4.6	144.1
POLY15	-2.5	82.8	1371.8

Performance with Real Data

Figures 5 and 6 show two examples of reasonably performing configurations of both WMA and GP when applied to real spectra from the BBQ system. From Fig. 5 one can see that the general tune estimates of the three algorithms are comparable in terms of accuracy. However, zooming-in (Fig. 6) we can see how the BQ algorithm is affected by the presence of the 50 Hz harmonics with large downward spikes which do not completely reach the harmonic frequency due to the Gaussian fit. It can also be seen from this figure that the WMA10 estimates seem to be more stable than those from both the BQ and GP algorithms.

CONCLUSION

A new approach based on the rejection of spectral points affected by 50 Hz harmonics is proposed to improve tune measurements at the LHC. In line with this approach, three methods were benchmarked against the presently implemented tune estimation algorithm which is known to underperform in the presence of these polluting harmonic components.

A Monte-Carlo simulation of second-order system frequency spectra was performed in order to generate spectra which mimic real beam spectra but for which the tune value is exactly known. The results obtained indicate that when properly configured both the WMA and GP algorithms can

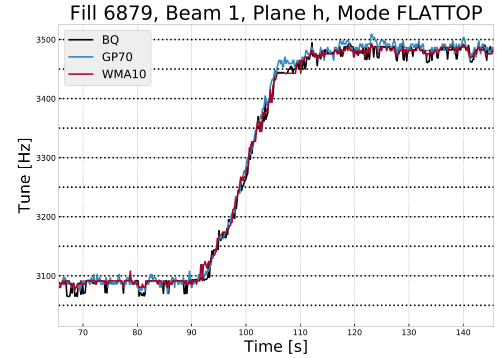

Figure 5: Tune trace plot with real data during the tune change when reaching FLATTOP.

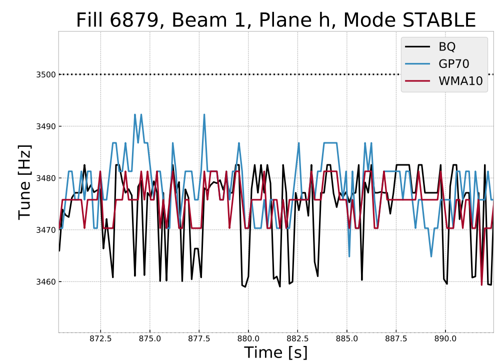

Figure 6: Tune trace plot with real data from STABLE beams.

achieve a better performance than the current algorithm in terms of accuracy and precision. Examples using real experimental spectra confirm this observation, with the WMA algorithm performing best.

This study will now be extended to more algorithms with the aim of selecting the most robust, accurate and precise one for real-time implementation on the LHC.

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