OPTIMIZATION OF BUNCH-TO-BUNCH ISOLATION IN INSTABILITY FEEDBACK SYSTEMS

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Abstract

Bunch-by-bunch feedback formalism is a powerful tool for combating coupled-bunch instabilities in circular accelerators. Imperfections in the analog front and back ends lead to coupling between neighboring bunches. Such coupling limits system performance in both feedback and diagnostic capacities. In this paper, techniques for optimizing bunch-to-bunch isolation within the system will be presented. A new method for improving the performance of the existing systems will be described. The novel approach uses a "shaper" filter in the digital signal processor to compensate for the imperfect response of the power amplifier and kicker combination. An objective optimization method to derive the optimal back end configuration will be presented and illustrated with measurements from several accelerators.

INTRODUCTION

Bunch-by-bunch feedback control of coupled-bunch instabilities is widely used in circular accelerators [1, 2, 3]. The formalism assumes that the correction signal for a given bunch only depends on the position of that same bunch over some number of past turns. In practice, implementations of the bunch-by-bunch feedback process necessarily have imperfections, which lead to coupling between bunches. Excessive coupling can limit achievable feedback performance or robustness. In this paper, methods for measuring, analyzing, and minimizing such coupling in practical systems are presented.

The next section describes typical hardware topologies for bunch-by-bunch feedback and highlights important sources of bunch-to-bunch coupling. Next, a novel approach for improving bunch-to-bunch isolation in the back end of the feedback system is presented, along with the experimental results.

HARDWARE

Historically, many different topologies and approaches have been explored in combating coupled-bunch instabilities [1, 3]. In the last ten years, however, the majority of the commissioned systems fall into one category — single pickup and kicker, with digital signal processing in the middle[1].

In a typical modern day bunch-by-bunch feedback system a single beam position pickup is used to observe bunch-by-bunch positions in one of three planes: horizontal, vertical, or longitudinal. Pickup signal is processed in the front end, then digitized by the controller. Correction signal, computed in real time, is converted to baseband analog signal and fed to the back end. Back end performs frequency translation, if necessary. The signal is then amplified and applied to the beam via a kicker structure.

One important point has to be made before we delve into the details of front and back end implementations. Feedback controller, also called baseband processor, operates at a sampling rate of $f_{\rm rf}$. It's natural to expect the input signal to be bandlimited within the first Nyquist band from DC to $f_{\rm rf}/2$ to prevent aliasing. In bunch-by-bunch feedback, however, aliasing is used to achieve high isolation between neighboring samples. Front end signal shape is designed to have fast rise and fall times, with the flat top occupying a fraction of the RF period. Similarly, in the back end, beam in the kicker samples at $f_{\rm rf}$ a waveform with, ideally, a larger bandwidth than dictated by Nyquist-Shannon sampling theorem.

Front End

Commonly used front end topology is sketched in Fig. 1. Beam position signal is normally generated by a pickup device, most frequently a capacitive button, sometimes a short stripline. That signal is then processed by a hybrid network. The hybrid serves two purposes: to separate orthogonal planes and to suppress large common-mode signals. Diagonal pickups are processed by a 4×4 hybrid network, also known as monopulse comparator in the radar world[2]. Four pickup signals, typically with large amplitudes, are subtracted in pairs to generate horizontal and vertical displacement signals, as well as the sum signal, used in the longitudinal plane. Output of a hybrid is fed to a bandpass filter, then amplified and mixed with a harmonic of the RF frequency. Baseband signal is filtered to remove high-frequency components. The resulting signal is then digitized by the baseband processor at the RF frequency.

All elements of the front end are potential sources of bunch to bunch coupling, but particular attention should be paid to the selection of bandpass and lowpass filters. In this context, fast settling of the impulse response is critical. As a bandpass filter it is customary to use analog finite impulse response (FIR) filters, also known as feedforward comb filters [1]. Bessel or Gaussian filters are good options for the lowpass design. The overall design goal is to optimize impulse response of the front end chain to settle within $T_{\rm rf}$. In practical implementations, carefully designed front end and

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[1] Incomplete list: ALS, BEPC-II, BESSY II, CESR-TA, DAΦNE, DELTA, Diamond, Duke SR-FEL, ELSA, ESRF, J-PARC Main Ring, MLS, PETRA III, Photon Factory, SOLEIL, TLS.

[2] Monopulse comparators are used in radars to separate signals from four antenna quadrants into azimuth, elevation, and sum.

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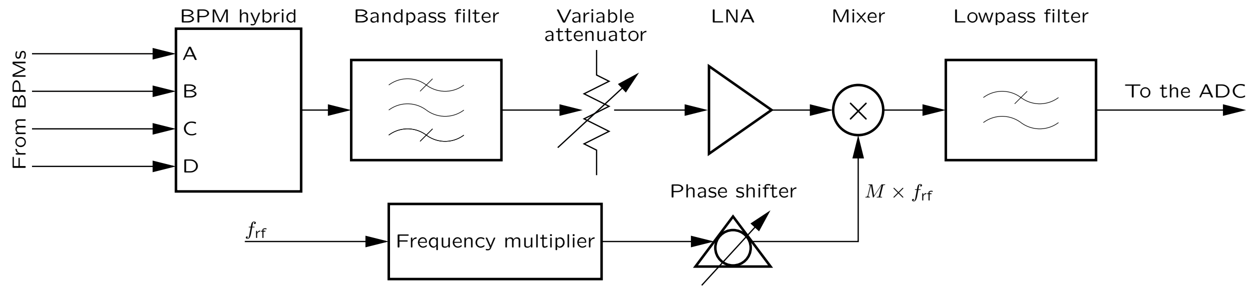

Figure 1: Front end signal processing chain.

baseband ADC combination can achieve 35–40 dB bunch-to-bunch isolation at 2 ns bunch spacing.

Another danger in the front end chain comes from the pickups themselves and their surroundings in the vacuum chamber. While front end detection frequency is normally placed below the cut-off of the vacuum chamber, to avoid propagating modes, impedances in the vicinity of the pickup can be sources of strong in-band signals. As these signals are detected in the front end, they can create strong coupling between bunches.

Back End

This discussion will focus on the baseband (transverse) back ends. Design goals in the back end are the same as in the front end — guaranteeing fast settling of the response. We start with the baseband output of a digital-to-analog converter (DAC). Ideal single bunch kick waveform is a rectangular pulse with T_{rf} duration. In practice, DAC outputs have finite rise and fall times, which should be kept as short as possible. Output of the DAC, amplified by a baseband power amplifier, drives a stripline kicker. Kicker shunt impedance increases with stripline length, as do rise and fall times of the kick waveform. As shown in Fig. 2, 30 cm (1 ns) long stripline has 2 ns fill time. Output waveform shown in the figure is the kick voltage, sampled by the passing bunch. With ideal drive waveform, stripline of length $cT_{\mathrm{rf}}/2$ produces no bunch coupling. That length is often picked by the designers as a good trade-off between bunch-to-bunch coupling and shunt impedance.

Now consider what is often the most limiting element in the back end chain — the power amplifier. 500 MHz storage rings usually specify amplifiers with 0.01–250 MHz bandwidth. Response of one, commonly used, such amplifier is shown in Fig. 3. Long rise time and extended ringing of the response produce significant coupling between bunches. Such coupling dramatically alters the behavior of the feedback channel, which is no longer bunch-by-bunch, even approximately. As a result, stable gain range and achievable damping are reduced [4]. Informal survey of installed transverse feedback systems operating with 2 ns bunch spacing shows the range of 10–20 dB for the bunch-to-bunch isolation in the back end.

In power amplifier selection it is important to pay attention not only to the bandwidth specifications, but also to its phase linearity. Since power amplifiers are usually quite non-linear, response should be checked in time as well as frequency domain. Since replacement of existing amplifiers is usually infeasible, active correction of the amplifier response has been explored. The goal is to pre-distort am-

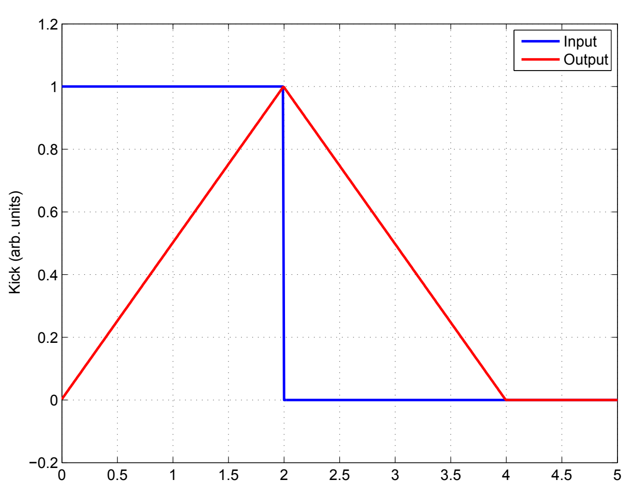

Figure 2: Response of a 30 cm long stripline to a 2 ns pulse.

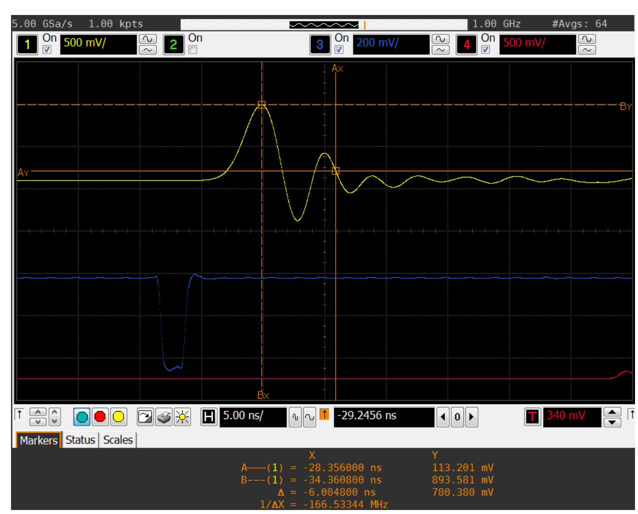

Figure 3: Response of Amplifier Research 250A250A amplifier (yellow) to a full-scale 2 ns kick pulse (blue).

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plifier input signal in order to obtain the desired response from the amplifier and the kicker. The back end shaper, described in the next section does just that.

BACK END SHAPER

Back end shaper is an FIR filter in the baseband processor, immediately preceding the DAC. The filter operates at the bunch crossing rate. Adjustable coefficients can be used to shape the DAC output in a way that improves feedback performance. Technical and experimental results presented here are based on the 3-tap shaper implemented in iGp12 baseband processor [5].

Design and Optimization

Shaper implemented in iGp12 is a 3-tap FIR filter, with two adjustable coefficients — the center tap is fixed at unity. In effect, the shaper can couple kick signal from a given bunch to the two neighboring bunches. In order to configure the filter, a minimax optimization procedure has been developed with the goal of minimizing the maximum back end coupling.

First of all, to set up the shaper it is necessary to quantify the back end response without it. Back end timing scan procedure has been adapted for this task. The baseband processor is configured to excite one bunch at the betatron frequency and the ring is filled with a single bunch. Next, the response of the beam is measured as the drive signal delay is scanned in 100 ps steps. The measured response signal is similar to the rectified version of the amplifier pulse response shown in Fig. 3, with one important difference — the scan with the beam includes the response of the stripline kicker.

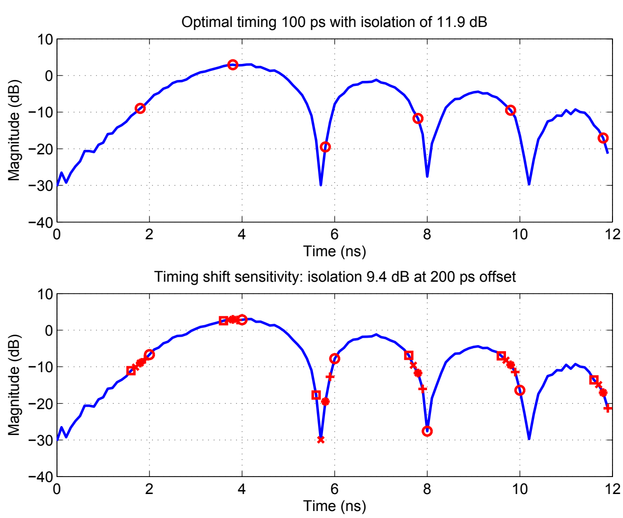

Figure 4: Raw back end response, BESSY II vertical plane.

Once the response is measured, a Matlab script is used to determine the optimal timing position. Optimality is defined in this context as the delay setting with the minimum back end coupling. Figure 4 shows the response curve measured in the vertical plane at BESSY II. Optimal timing offset of 100 ps is selected to equalize at -11.9 dB the coupling to two buckets: one immediately preceding the main kick and one 6 ns later. The bottom curve explores the timing drift sensitivity, showing that at 200 ps offset from the optimal position the coupling rises to -9.4 dB.

From the measured magnitude response, a linear-scale pulse response is computed by inverting signal sign at the minima. This estimated pulse response is then fed to an 3-parameter constrained minimax optimization. The parameters are two shaper coefficients C_0 and C_2 and the timing offset T. The optimizer convolves copies of the back end pulse response to compute the effective excitation waveform. This assumes linear behavior in the back end.

Experimental Results

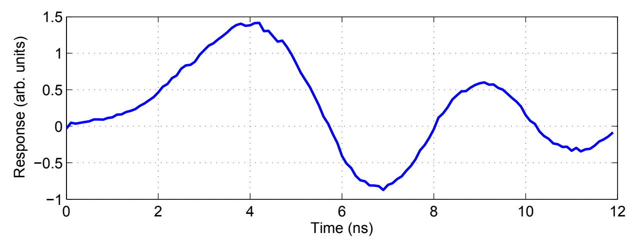

Figure 5: Computed BESSY II vertical pulse response.

Procedure, described in the previous section, has been tested at two light sources — BESSY II and TLS. Let us discuss first BESSY II experiments. From the measured back end response (Fig. 4), linear scale pulse response shown in Fig. 5 is computed. Next, manual search in the C_0, C_2, T space was performed, leading to shaper FIR coefficients of $[-0.3\ 1\ 0.15]$ and $T = 1900$ ps. Figure 6 shows a comparison of the measured and the computed responses with these settings. The curves agree very well in the main four lobes, only diverging at points where the measurement runs into the noise floor or the computed curve has insufficient response data for proper convolution. Measured coupling in this case is -18.6 dB, in excellent agreement with the computed -18.4 dB. Running the actual optimizer with the impulse response shown in Fig. 5 results in the coefficient vector of $[-0.31\ 1\ 0.42]$ and $T = 1800$ ps. Coupling drops farther to -23.4 dB. One worry in such optimization is that we are "hiding" neighboring bunches in the notches, so that timing shifts could lead to even worse coupling than that of the uncorrected back end. Optimized response degrades to -12.3 dB coupling at 200 ps offset — better than the uncorrected response at optimal timing.

At the TLS, shaper experiments were performed in the horizontal plane. Measurement of the uncorrected back end response is presented in Fig. 7a. Both the shape and the objective coupling results are similar to those from BESSY II — not too surprising, given that the machines use similar power amplifiers. The measurement is much noisier than that from BESSY II, due to large horizontal tune variation. Optimizer produced a coefficient vector of $[-0.32\ 1\ 0.24]$

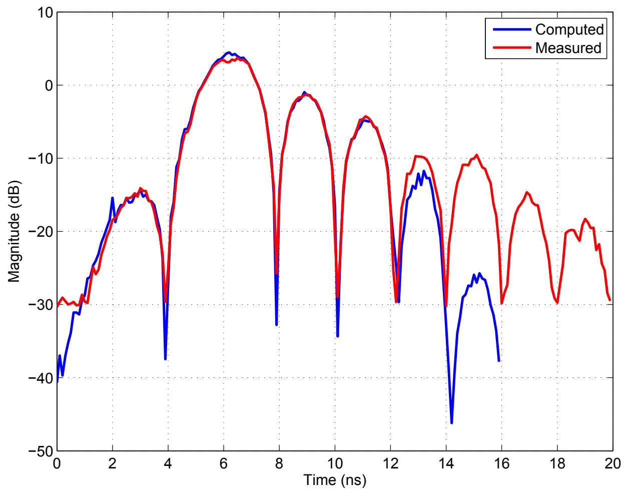

Figure 6: Measured and computed back end responses with the shaper.

and projected coupling reduction to −23.2 dB. Shaper-corrected response, shown in Fig. 7b, achieves −18.8 dB. The likely reason for the discrepancy is that the optimization process is quite sensitive to the quality of the initial response measurement.

As the two examples above show, optimized back end shaper can reduce bunch coupling from −12 to −18 dB. Empirically, this improvement marks the difference between robust bunch-by-bunch damping performance with predictable tuning and the marginal one. For example, at the TLS, with the uncorrected output set to 700 ps it was impossible to achieve full stability. Increasing the feedback gain to damp the unstable modes lead to the excitation of the high-frequency eigenmodes around 250 MHz due to the large loop phase excursion generated by the back end coupling. With the optimized shaper coefficients, the system behaved as expected, resulting in a large stable gain window. At BESSY II, attempts to excite a single bunch in the middle of the bunch train for bunch cleaning[3] produced significant coupling to the following bunches, driving them to large oscillation amplitudes. With the empirically optimized shaper setup (−18.6 dB coupling) excitation of neighboring bunches was nearly non-existent.

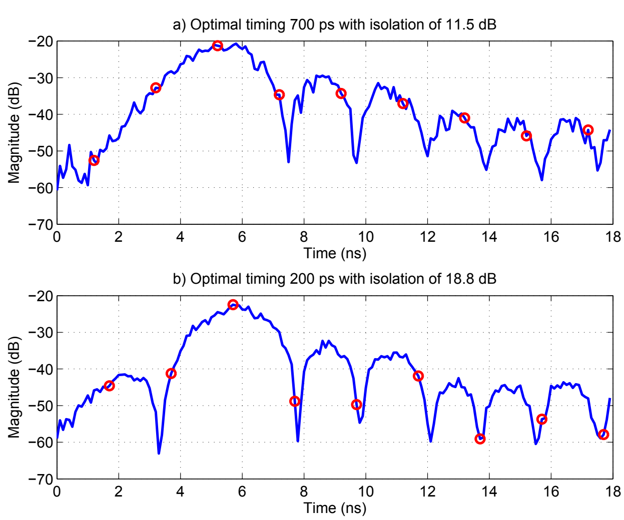

Figure 7: a) Uncorrected back end response, TLS horizontal plane; b) With optimized shaper correction.

Future Directions

Further efforts should focus on improving the response measurement procedures and on alternative optimization approaches. In particular, currently selected optimization goal is to minimize maximum coupling. Another promising option is to use the response of the distortion FIR [4] and to minimize deviations from the linear phase response. Another important area to investigate is the long term stability of shaper configurations, as well as dependence on signal levels, amplifier saturation, and temperature.

SUMMARY

Bunch-to-bunch isolation in the multibunch feedback signal chain is important for system performance. In this paper, commonly used signal processing topologies were discussed, pinpointing the possible sources of parasitic signal coupling. Experience shows that the overall coupling is typically dominated by the power amplifier.

A digital pre-distortion filter has been successfully tested at several bunch-by-bunch feedback system installations. The filter implementation, together with the measurement and optimization procedure has been shown to halve the parasitic bunch-to-bunch coupling in transverse feedback applications.

ACKNOWLEDGMENTS

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[5] `http://www.dimtel.com/products/igp12`.

[3] For the selected bunch the feedback correction is turned off and the full-scale excitation at the betatron frequency is applied.

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