OVERVIEW OF SYSTEM SPECIFICATIONS FOR BUNCH BY BUNCH FEEDBACK SYSTEMS

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Abstract

Bunch-by-bunch feedback control of coupled-bunch instabilities has become a ubiquitous feature of storage rings, light sources and colliders. Specifying the requirements for these systems demands knowledge of the instability sources and the accelerator operating parameter space. System requirements include the necessary loop gain and bandwidth, kick voltage, and the overall noise floor. Based on these specifications one can select the system BPMs, processing algorithms, power amplifiers and kickers and make tradeoffs of system cost against necessary performance. Analytical methods and experimental techniques are applied to practical examples to illustrate pragmatic and intelligent choices in this specification process. The approach involves experimental characterization of the accelerator at low or moderate beam currents. Measurements are used to calibrate a parametrized analytical beam dynamics model which can be then extrapolated to nominal beam currents with confidence. Example results from several recent installations are presented to highlight the measurements, the model predictions, and the achieved system performance.

INTRODUCTION

Active control of coupled-bunch instabilities in lepton storage rings is widely used in modern day accelerators. Application of the bunch-by-bunch feedback formalism allows designers to create robust and efficient damping systems. Analysis methods presented in this paper will help accelerator physicists and engineers make informed decisions when specifying system components.

The majority of instability control systems currently in development and commissioning rely on digital signal processing technology, though analog systems are also possible [1, 2]. The focus of this paper is on control of dipole motion in lepton storage rings, even though many feedback techniques and analysis methods presented here are applicable to the control of higher order coupled bunch instabilities or to the hadron machines.

To understand these systems, the overall bunch-by-bunch feedback architecture is presented, followed by analysis of key individual system components and their contribution to the overall system performance. Methods and analysis techniques to investigate the effects of imperfections and errors are illustrated. The trade-offs in system design, including gain partitioning and power stage sizing are explored.

BUNCH-BY-BUNCH FEEDBACK ARCHITECTURE

In a bunch-by-bunch feedback process, correction signal for a given bunch is determined by the past history of motion of that bunch. This approach reduces the feedback computational requirements from $O(N^2)$ to $O(N)$ where N is the number of bunches in the ring. One can represent the beam as a multi-input multi-output (MIMO) system, where the inputs are the correction kicks applied to the individual bunches, and the outputs are the bunch positions. The beam is an MIMO dynamic system with N inputs and N outputs. In frequency domain such system can be represented by an $N \times N$ transfer function matrix. Bunch-by-bunch feedback system is an $N \times N$ diagonal transfer function matrix. Typically we apply the same feedback to each bunch, so the feedback matrix can be written as $H(s)\mathbf{I}_N$ where $H(s)$ is the feedback response for each bunch and $\mathbf{I}_N$ is an $N \times N$ identity matrix. Mathematical analysis shows that uniform bunch-by-bunch feedback applies the feedback transfer function $H(s)$ to each eigenmode [3, pages 26–32]. Thus, a MIMO system can be decomposed into N eigenmodes, each with identical feedback loop around it. Such decomposition greatly simplifies system modeling as well as the analysis of performance limitations.

Unfortunately, idealized mathematical models are rarely seen in the real world. Physical system implementation inevitably introduces imperfections that limit the system performance. The impact of these imperfections can be understood through study of a typical system topology, and examination of key individual elements.

A typical bunch-by-bunch feedback channel, illustrated in Fig. 1, includes analog front- and back-ends as well a digital feedback controller or processor, operating at the bunch repetition frequency.

Front End

Analog front-end of the feedback system processes BPM outputs to generate horizontal or vertical orbit error signals in the transverse planes or the sum signal in the longitudinal plane. Resulting signal is then amplified, filtered, and downconverted to baseband.

Signal shaping is performed in the front-end with two (competing) objectives: obtaining flat pulse top and minimizing bunch to bunch coupling. Flat pulse top is needed to reduce system sensitivity to sampling clock jitter and drifts. However too long a pulse can extend beyond one bunch period and interfere with the neighboring samples.

For an in-depth discussion of front-end architectures and

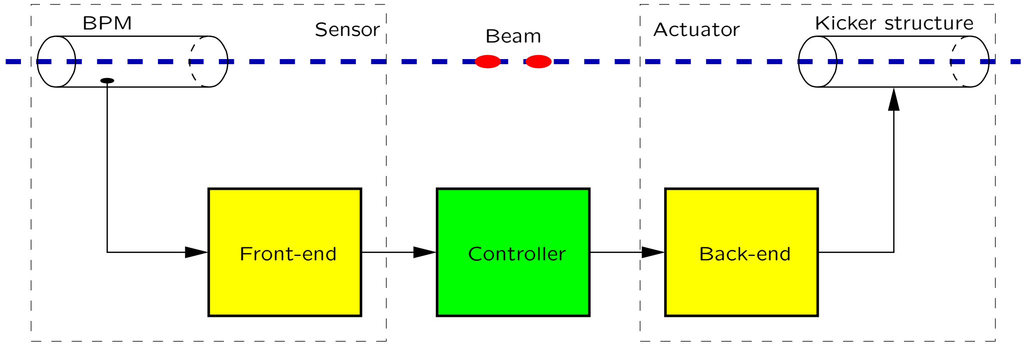

Figure 1: Block diagram of a bunch-by-bunch feedback system.

tradeoffs the reader is referred to [2, pages 482–486].

Controller

Controller is typically implemented as a digital signal processor (DSP) running at the bunch repetition rate. Samples of individual bunches from multiple turns are used to calculate the correction signal. FIR filtering is most commonly used for such calculation. Output of such a filter is a convolution of the past inputs with the filter coefficients, described by $q[n] = \sum_{m=0}^{M-1} c_m u[n-m]$. The main requirement for the feedback controller is to generate a net $90°$ phase shift at the dipole oscillation frequency, since the system senses position and acts on energy and angle in longitudinal and transverse planes respectively. In addition, feedback controller generates a bandpass response around the bunch oscillation frequency to avoid wasting amplifier power on out of band signals. Most critical of these is the DC component due to physical or electronic orbit offsets.

Performance limitations due to the DSP typically stem from FIR filter length limitations, coefficient quantization, and overall gain partitioning. Controllers for the longitudinal plane are particularly challenging due to low synchrotron frequencies. In order to generate $90°$ phase shift the impulse response has to span at least a quarter of the oscillation period.

Back End

Back-end implementations are primarily defined by the kicker type used. Differentially driven stripline kickers are used in the transverse plane [4]. Their frequency response has $\mathrm{sinc}(2l/cf)$ frequency dependence where l is the stripline length. Such kickers require baseband excitation, so the correction signal from the DAC only needs amplification. Longitudinal kickers usually have bandpass response in the 1–1.5 GHz range, so the correction signal needs to be frequency translated from baseband before power amplification. Dual and single-sideband modulators have been successfully used for such frequency translation [5, 6]. In the back-end design we are pursuing similar objectives as in the front-end: maximum bunch decoupling and wide pulse. The latter is desirable in order to maximize high-frequency kick amplitude generated by necessarily bandlimited power amplifier and kicker combination.

Signal Sampling

In a bunch-by-bunch feedback system, critical analog signals are present in the front-end — up to the ADC — and in the back-end starting from the DAC. In both cases the signals are sampled: by the feedback processor ADC in the front-end and by the beam in the back-end. Even though feedback kicker typically has finite length, beam interaction with the kicker structure can be equivalently represented as an linear time-invariant response with a well-defined transfer function, followed by sampling. Due to this similarity, analysis approaches to front- and back-ends are nearly identical.

In the ideal world, each signal is perfect, that is the sensed position of one bunch is only presented in one sample and does not affect the neighboring bunch signals. Similarly, bunch correction kick should only interact with the desired bunch. However, unavoidable imperfections such as limited bandwidth, finite slew rates, reflections, and others stretch the signals in time domain beyond one bucket.

Time and Frequency Domains

Many systems encountered in signal processing are linear, time invariant (LTI). For such systems time and frequency domain responses are linked by Fourier transform, with the frequency transfer function being a transform of the system's impulse response. Due to sampling, bunch-by-bunch feedback channel is not time invariant. Consequently, familiar fixed relationship between frequency and time domain responses does not hold. In analyzing performance limiting imperfections in the front-and back-ends both time domain and frequency domain analysis is needed.

PERFORMANCE LIMITATIONS

In frequency domain the beam can be represented as a collection of N independent harmonic oscillators, resonant at the betatron or synchrotron sidebands of the revolution harmonics [7]. Complex eigenvalues define growth or damping rates and oscillation frequencies. In this representation, ideal bunch-by-bunch feedback system is decomposed into N identical controllers acting on each eigenmode. Physical implementation errors can be analyzed in the form of constant per-mode gain and phase errors. In order to understand how these errors affect the system performance we will consider the gain window. To quantify the actual errors it is useful to introduce the equivalent distortion filter concept.

Gain Window

Consider a single unstable eigenmode with an appropriately phased feedback controller around it. Let us sweep the loop gain starting from zero. A root locus plot, shown in Fig. 2 illustrates this process. In such a plot, system eigenvalue locations are plotted on the complex plane as a function of the loop gain. Real part of the eigenvalue corresponds to the growth (if positive) or damping (negative) rate, while the imaginary part determines the oscillation frequency. Starting from the modal eigenvalue in the right half plane (gain of 0), the locus crosses the imaginary axis at the gain of 7.5. Further gain increase produces more damping, but only up to a point. Beyond the maximum damping point, the closed-loop poles turn around and start moving towards the imaginary axis. At a gain of 240 one of the poles crosses the imaginary axis, making the system unstable again. The gain window is defined as the difference between minimum and maximum gains in decibels.

For the idealized bunch-by-bunch feedback, minimum gain is proportional to the fastest growth rate. Maximum gain mostly depends on the feedback group delay. The gain window can be expanded by using shorter feedback filters with lower group delay. This theoretical gain window is then reduced by system imperfections. Modal gain and phase errors affect the gain window in different ways. Reduced gain is only problematic if it affects an unstable

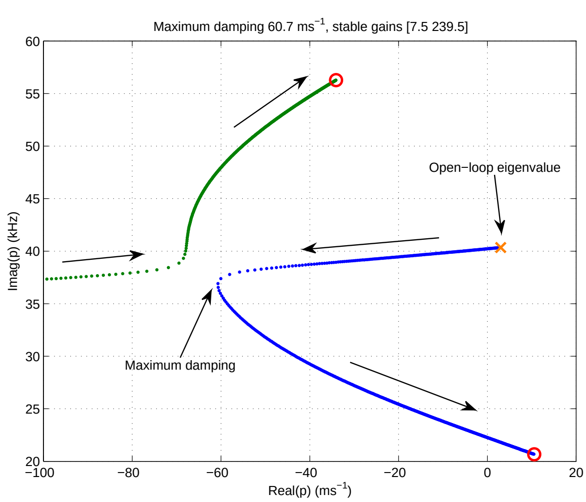

Figure 2: Root locus plot for a single eigenmode showing dominant eigenvalues.

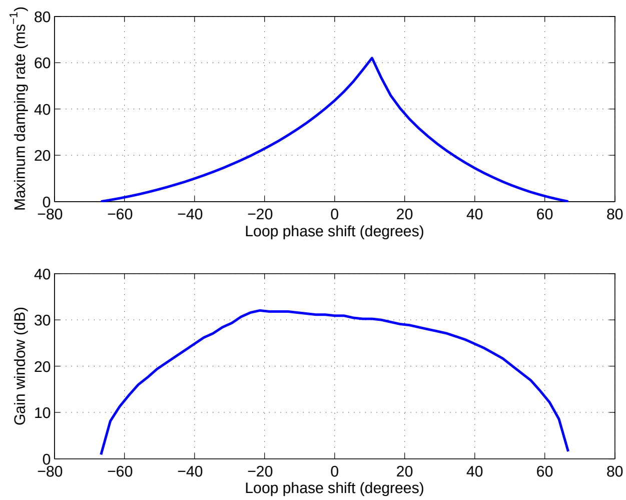

Figure 3: Simulated performance limits for a longitudinal feedback system in the BEPC-II positron ring. The maximum damping rate (top) and the gain window (bottom) vs. the feedback loop phase shift.

mode and the reduction is sufficient to raise the overall minimum stabilizing gain. Gain peaks in the loop response translate, however, directly into the gain window reduction.

Figure 3 shows the simulation results for BEPC-II longitudinal feedback [8]. Maximum achievable damping rate is determined by sweeping the feedback loop gain and finding the value that maximizes the closed-loop damping of the dominant eigenvalues, as measured by the real parts of the computed closed-loop poles. In order to find the gain window, we identify the gain range for which all closed-loop poles are in the left half plane. Phase shift value of zero is selected to maximize the phase margin — the minimum change in the loop phase that makes the system unstable. For this particular eigenmode the phase margin is 67 degrees. Clearly, there is a trade-off between the optimal gain window size and the maximum damping rate. However large phase shifts in the feedback channel cause dramatic reduction in both parameters.

For a typical storage ring, the gain window ranges from 20 to 40 dB. As a rule of thumb, a minimum gain window of 12 dB is needed for robust system operation. Challenging situations arise in machines where fast growth rates are combined with low oscillation frequencies, typically in the longitudinal plane [9].

Equivalent Distortion Filter

In an ideal situation, analog signals in the front- and back-ends are such, that after sampling, single-bunch signal appears only in one sample. In order to analyze the effect of signal coupling, let us introduce the concept of equivalent distortion filter. Samples of the analog signal at the bunch repetition rate form coefficients of an FIR filter. In the time domain, ratios of filter coefficients indicate the coupling from bunch to bunch. Frequency domain re-

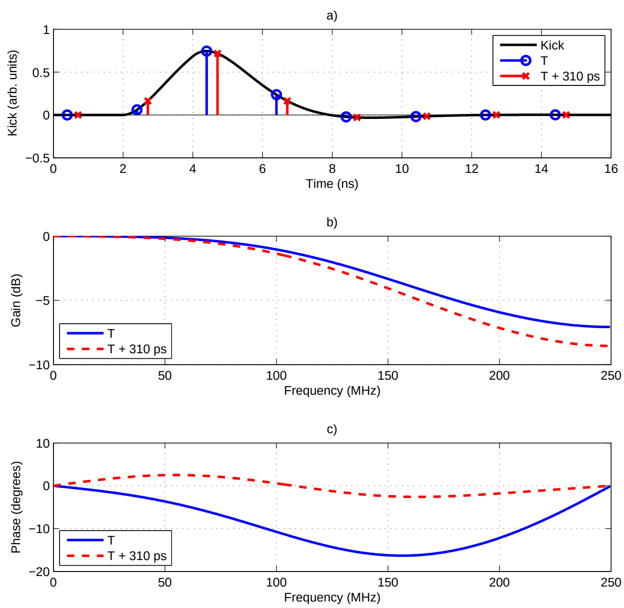

Figure 4: a) Simulated kicker signal (driven by a 2 ns rectangular pulse) and and its sampling by the beam at two relative timing settings; b) Magnitude response of the distortion FIR; c) Phase response of the distortion FIR.

sponse of the distortion FIR, evaluated at the eigenmode frequencies, defines the gain and the phase errors of the individual modes. Both the front-end and the back-end sampling processes form these distortion FIR filters. A convolution of their coefficients in the time domain or a product of their frequency responses must be evaluated to obtain overall modal gain and phase errors.

Figure 4 shows the simulated kick output generated by a 2 ns rectangular pulse. Nominal timing T is chosen to sample the peak of the kick waveform. In this case the coupling to the next bunch is around 30%. Adjusting the relative timing between the kick and the beam by 310 ps allows us to equalize the coupling to the preceding and the following bunches at 23% level. As magnitude and phase responses of the distortion FIR show, relative timing between the analog signal and the sampling clock is very important. By shifting off the peak we are trading off 1.5 dB of gain at the highest frequencies for a reduction in peak loop phase error from 16.3 to 2.6 degrees.

EVALUATION AND SIZING

This section presents a procedure for intelligently selecting feedback system components for an existing storage ring. The kicker and the power amplifier are two of the most expensive elements of a bunch-by-bunch feedback system, usually with long procurement lead times. Replacement of these components is time consuming and expensive. Procedure described below helps avoid costly mistakes.

We start from making instability measurements in a temporary, improvised feedback setup. Collected information is used to calibrate a numerical closed-loop model of the coupled-bunch instabilities and the feedback. Such measurements are typically performed at relatively low beam currents close to the instability threshold due to limited gains and kick amplitudes. The model can then be used to simulate system performance at the nominal machine operating conditions and to define required kicker shunt impedance, amplifier power and bandwidth. For further information on beam and feedback modeling the reader is referred to [3, chapter 5].

Gain and Kick

It is important to pay attention to the difference between feedback gain and the peak kick. Peak kick is the maximum momentum change that the feedback system can induce on the beam in a single turn. Peak kick requirement defines the necessary kicker shunt impedance and amplifier power. It is determined by the transient and steady-state disturbances that the feedback system must reject. Feedback gain is defined as the ratio between the amplitude of beam oscillation and the amplitude of the resulting correction kick. Necessary feedback gain is determined by the instability growth rates and the overall gain window.

Often, these two parameters are treated as rigidly linked, with the ratio of peak kick to the disturbance amplitude taken as the feedback gain. However such approach is conservative — equivalent to the requirement that the feedback system output never reaches saturation. Let us consider what happens in saturation. Suppose our feedback gain is ten times higher than the conservative value $g_0 = K_{\max}/u_{\max}$ where K is the kick amplitude and u is the input disturbance amplitude. For disturbances below $u_{max}/10$, the system operates in the linear regime. At larger disturbance amplitudes, output kick signal no longer increases in the peak-to-peak sense. Thus, the loop gain g drops, but it does not drop as $K_{\max}/u$. As the system goes into saturation, the kick waveform gradually transitions from a sine to a square wave. Amplitude of the fundamental in the saturated waveform is up to 2 dB higher than the sinusoidal signal. When disturbance amplitude reaches $u_{\max}$, the loop gain is roughly $4g_0/\pi$.

Bunch-by-bunch feedback not only stabilizes the coupled-bunch motion, but also acts to reject external disturbances in proportion to $1/g$. Thus, using loop gain higher than g_0 is likely to reduce the steady-state beam motion.

An obvious conclusion from the discussion above is that operating at gains above g_0 is a net benefit. A more difficult question is whether the feedback can be configured with g_0 below the minimum stabilization gain and still suppress the coupled bunch motion. To answer this question one needs to investigate the nature of the expected disturbances. If they affect a fraction of the stored beam — typical for the injection transients — saturation for that subset of bunches is counteracted by the linear high-gain opera-

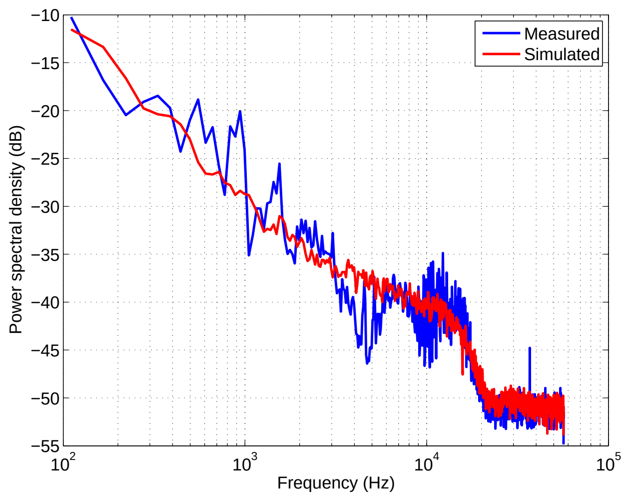

Figure 5: Measured and simulated longitudinal steady-state motion in DELTA.

tion of the feedback for the rest of the ring. Overall gain for the unstable modes is a weighted average of the gains from the saturated and linear portions of the fill pattern. That gain must be kept above the stabilization minimum.

Gain Partitioning

There is a natural partitioning of gain into front-end, controller, and back-end components. Front-end gain is limited by two factors — need to fit steady-state orbit offsets in the ADC range and the noise floor. To maintain signal integrity in the back-end, its gain is matched to the full-scale output of the controller DAC. Saturation in a digital bunch-by-bunch feedback system should only take place in the controller in a perfect digital saturator. Gain of the DSP section is constrained by the front-end noise and the ADC quantization noise.

Component Sizing

In order to configure the numerical beam and feedback model the following measurements are needed: instability modal patterns; growth and damping rates; tune shifts; steady state residual motion; transient excitations from the injection.

As the first step, the model is adjusted to match the growth and damping rate measurements, setting the overall gain value. By factoring out known front-end calibration factors, DSP gain, and power amplifier output, one can estimate the shunt impedance of the improvised kicker.

Next, multiple steady-state noise source are added to the model in order to match the measured disturbance patterns. Figure 5 shows the steady-state noise spectrum measured at DELTA [10] and the spectrum of the simulated bunch motion. Both the spectral shape and the overall RMS power are matched.

Growth rate and tune shift measurements at different beam currents are then used to determine the growth rate dependence on beam current and to extrapolate to nominal machine operating currents. Such extrapolation is only meaningful if the driving impedances do not change with beam current. If the impedances do change, such as RF cavity fundamental-driven longitudinal motion in heavily beam loaded machines, further modeling is needed to calculate the growth rates and the tunes.

Finally, we can run the numerical model for the nominal beam currents, using the extrapolated growth rates, oscillation frequencies, and noise levels. For extrapolating the perturbations it is best to combine the measurements made at low currents with some analytical insight into the sources of these perturbations and their behavior as a function of beam current. The resulting model can then be used to determine the required kick amplitude. As a rule of thumb, for robust operation closed-loop damping rates should at least equal the open-loop growth rates (gain margin of 6 dB).

SUMMARY

Bunch-by-bunch feedback is an important tool for the accelerator physicist. Understanding the relationship between time and frequency domains in such systems is critical for successfully designing and configuring bunch-by-bunch feedback. Combination of experimental measurements and modeling provides a powerful way to optimize critical system elements — power amplifiers and kickers.

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