LIMITATIONS OF MULTIBUNCH FEEDBACK SYSTEMS AND EXTRAPOLATION

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Abstract

In recent years, multibunch feedback systems which can handle bunches with 10-ns spacing (or shorter) are working at several accelerators around the world. The number of bunches stored in some of these accelerators is very large, on the order of 1000. Due to the large scale and fast processing requirements, the designs of the feedback systems are quite different from those of 10 years ago. In this report, we review the features of these feedback systems and give several examples. In addition, we give some examples of powerful beam-diagnostics system based on these feedback systems.

1 INTRODUCTION

Some ten years ago, bunch feedback systems were designed and implemented when instabilities were observed, and feedback damping was considered to be indispensable for the operation of a ring. In recent years, however, in some rings called "factories," design and implementation of the feedback systems are done in parallel with those of the ring itself. This suggests that the bunch feedback systems are playing more important roles in such rings.

In this report, we review the characteristics of the bunch feedback systems which have been recently commissioned in the factory machines. In addition, we will give a brief introduction to time-domain beam-diagnostic systems which are based on modern digital feedback technology.

2 WHAT IS A BUNCH FEEDBACK SYSTEM?

2.1 Multibunch instabilities

Before going into the main part of this report, we review multibunch instabilities and bunch feedback systems. Imagine a beam-bunch circulating in a ring at a speed very close to that of light. Since it is charged, it inevitably excites electro-magnetic fields behind it, i.e., it deposits energy in each part of the accelerator structure. What kind of field is excited strongly depends on the nature of the structure. The excited field will eventually be damped, but when the life time of the excitation is longer than the time-interval of the bunch-passage, it affects the motions of bunches which later pass through the structure (the wake force). The second bunch, again, deposits energy in the structure. A chain of these passages can cause unwanted transverse and/or longitudinal oscillations of bunches, if several unfortunate conditions are satisfied.

When multiple bunches are stored in the ring, and consequently the bunch-spacing gets shorter, the probability of magnifying of oscillations is greater. Through the wake force, bunches stored in the ring interact between themselves. The correlative instabilities thus excited are called multibunch (or coupled-bunch) instabilities.

We can understand the betatron/synchrotron oscillations as quasi-harmonic oscillations; that is, the motions of a bunch must obey the following equation :

$$\ddot{x}_i + \omega_0^2 x_i = F_w, \tag{1}$$

where x_i is the transverse/longitudinal position-error of the i-th bunch and ω_0 the betatron/synchrotron frequency. The driving term F_w in this case is the wake force due to the trapped energy in the structure.

A classical example of the structures which are likely to excite such instabilities is an accelerating cavity; its higher-order modes sometimes cause a growing oscillation of bunches. Recently, another kind of "structure" is reported, that is, electron clouds. In CESR at Cornell[1], electrons captured in a potential interact with the circulating bunches and a horizontal multibunch instability is excited. Similar phenomena, but in the vertical plane, are also observed at the Photon Factory[2] at KEK and at BEPC[3] at the Institute of High Energy Physics, China. A crowd of ions surrounding the negatively-charged beam is also a special case of a "structure" sometimes causing instabilities.

2.2 Feedback damping

The mission of a bunch feedback system is to damp these oscillations. The usual way to damp the motion governed by Eq. (1) is to add a term proportional to the velocity, $\dot{x}$:

$$\ddot{x}_i + 2\eta\dot{x}_i + \omega_0^2 x_i = F_w,$$

with η being the damping coefficient. It is, however, hardly possible to know the "velocity" in the case of the betatron/synchrotron oscillations. In place of that, we can use the "delayed position", $x(t-\Delta t)$. For the sinusoidal functions, differentiation and origin-point displacement by $\pi/2 + 2n\pi$, with negation after that, are mutually equivalent. Then the equation of motion can be expressed as

$$\ddot{x}_i(t) - 2\eta x_i(t - (2n+1/2)\pi/\omega_0)) + \omega_0^2 x_i(t) = F_w. \tag{2}$$

This equation tells us that the function of the feedback system is to create a force corresponding to $2\eta x(t-\Delta t)$. This statement implies that we are not concirned with the detailed characteristics of F_w; whatever F_w is, we can damp the oscillation via the term $2\eta x(t-\Delta t)$, if the gain of the damping ($\propto \eta$) is high enough.

Feedback systems designed based on Eq. (2) are called bunch-by-bunch (time-domain) feedbacks. In designing bunch-by-bunch feedback systems, the designers implicitly ignore the nature of the term F_w except for its total strength. Consequently, they must prepare a system which can handle any frequency range of oscillation sources. In this sense, the term *bunch-by-bunch* feedback is sometimes used for the *full-range* feedback system.

2.3 Consideration in the frequency domain

Now we consider cases where we have some knowledge of F_w, in particular its frequency responce. We move to the frequency domain by making the Fourier transform of Eq. (1):

$$-\omega^2 X_i(\omega) + \omega_0^2 X_i(\omega) = \tilde{F}_w(\omega), \tag{3}$$

where $X_i(\omega)$ and $\tilde{F}_w$ are the Fourier transforms of x_i and F_w. As a simple example, we assume $\tilde{F}_w$ has a sharp peak at ω_1. The task of the feedback designer is to add a feedback term $F^1_{fb}(\omega_1)$ to the last equation in order to cancel out $F^1_w(\omega)$. Then the equation of motion including the feedback becomes

$$-\omega^2 X_i(\omega) + \omega_0^2 X_i(\omega) = \tilde{F}^1_w(\omega) - \tilde{F}^1_{fb}(\omega_1) \tag{4}$$

Feedback systems designed with using this equation are called mode-by-mode (frequency domain) feedbacks. Note that the feedback term is created from the signal from all the bunches in a ring, while that in the bunch-by-bunch system is made of the signal of only one bunch.

In modern factory-machines, the number of bunches is large and the feedback designers have only poor knowledge of F_w at the design stage of the ring. For these machines bunch-by-bunch systems are adopted. Hereafter, our discussions will be done considering the bunch-by-bunch feedback systems.

2.4 Bandwidth required for the system

In the above discussion, we regarded the position-measurement and the kicking as continuous actions on a beam-bunch. Actually, the monitor and the kicker are positioned at a certain point in a ring and these actions are performed discretely. When a single bunch is stored in a ring, the monitor ”sees” the bunch every revolution period and the observed pattern repeats itself with the frequency of the revolution, f_r. When N bunches (with the same population and equal spacings) are stored, the monitor sees the repeated pattern of the frequency of Nf_r, which is the bunch frequency. The system is observed at the sampling rate of the bunch frequency.

In general, when the time-domain information is cyclic, the corresponding information in the frequency domain is also cyclic with the interval of the sampling frequency. Moreover, the non-redundant information lays within half of the sampling frequency. From this consideration, the feedback system must have the bandwidth of, at least, half the bunch frequency.

2.5 Phase rotation techniques

According to the previous discussion, the betatron phase rotation from the feedback monitor to the kicker must be $\pi/2 + 2n\pi$, with n an integer. Within one turn, the betatron phase advance is $2n\nu - \Delta\mu$, where ν is the tune of the ring and $\Delta\mu$ the phase-slip between the monitor and the kicker. By carefully choosing $\Delta\mu$ we can design a basic type of transverse feedback system.

However, it is not always possible to adjust $\Delta\mu$ to its ideal value from various reasons. An alternative way to achieve the required phase rotation is the vectorial sum technique. As shown in Fig. 1, two pickup-receiver systems are prepared and the signals are summed with appropriate coefficients, $C1$ and $C2$ in the figure.

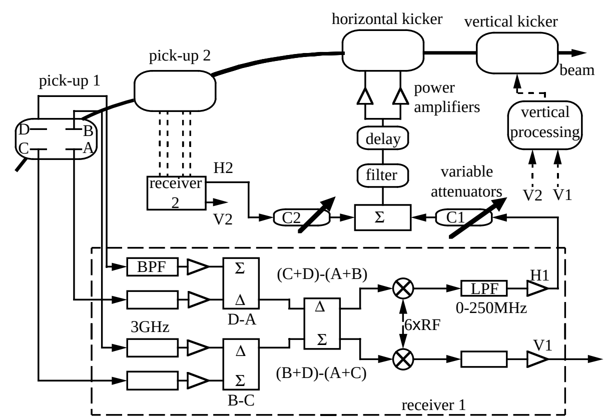

Figure 1: A block diagram of the ALS transverse feedback system[4].

Another way of creating the $\pi/2 + 2n\pi$ phase rotation is to use a multi-turn delay, as realized in the CESR transverse feedback system[5]. It is not difficult to find the number of turns after which the total betatron phase rotation has a value close to $\pi/2$ mod(2π), as explained in Ref. [6].

2.6 Filtering techniques

In the actual design of the feedbacks, it is important to consider noise reduction, particularly, elimination of DC component of the signal. One of the most simple methods of the DC-reduction is the NSLS transverse damper system at BNL[7]. As shown in Fig. 2, the one-turn delay line system to eliminate the DC component can be understood to be an analog 2-tap filter. Sometimes this type of filter is called a *notch filter*.

For the multi-turn delay scheme, this DC-eliminating concept can be used. This technique is called the 2-tap filter method and is discussed in detail in Ref.[6].

3 HARDWARE COMPONENTS

A bunch feedback system consists of (1) a *position detection part*, (2) a *signal processing part* and (3) a *kicker part*. Each part must have sufficient bandwidth.

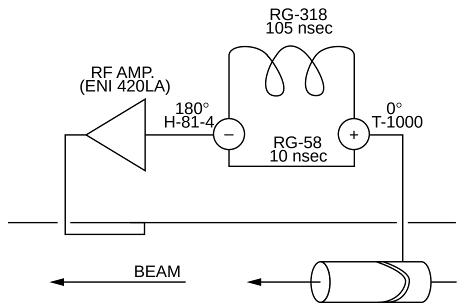

Figure 2: A schematic drawing of the NSLS transverse damper system.

3.1 Position detection part

The position detection part, consisting of pickups and a receiver, generates a pulse whose height is proportional to the position error. Essentially, this part is a bunch-by-bunch position monitor. However, sometimes the output is not proportional to the error itself but is multiplied by the bunch intensity, as a consequence of the omission of the normalization by the bunch current. An example of such position receiver is shown in Fig. 1 (in the dashed-line box).

3.2 Signal processing part

The function of the signal processing part is to delay the signal and filter out noise. If the ring is larger, and the required delay is longer (typically in the longitudinal plane), digital systems are commonly used. Naturally, the front-end of a digital signal processing system is an Analog-to-Digital Converter (ADC). Several companies deliver 500Msamples/s ADC with resolutions of 8 bits. Recently, 1Gsample/s are also commercially available.

The central part of the signal processing system is the fast digital electronics behind the ADC. It performs the delay and digital filtering. The logic implemented in the system is usually a Finite Impulse Response Filter (FIR). By carefully choosing the filter-parameters of the FIR, the desired filter function is obtained.

A typical example of such electronics systems with very short bunch-spacing is that developed at SLAC for the longitudinal feedback. It was implemented first in the ALS at LBNL and after that it was extended and installed at PEP-II. The hardware architecture of this system is shown in Fig. 3[8]. In this system, a down-sampler is implemented to control the sampling rate for relatively slow synchrotron oscillation. The main part of the processing unit is a farm of digital signal processors (DSPs) and is very flexible. In fact, this system is now used at 6 sites[9] around the world, at PEP-II, ALS, DAFNE, SPEAR BESSY II[10] and PLS[11].

Another example of the signal processing systems is that developed at KEK for the KEKB rings[12]. A block diagram in Fig. 4 depicts the structure of the system. This system covers both transverse and longitudinal systems. The

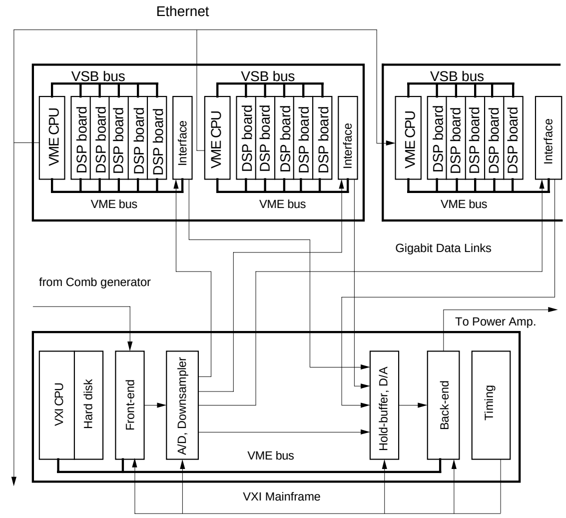

Figure 3: System hardware architecture of the longitudinal feedback systems at ALS.

main feature of the system is that it uses custom Ga-As LSIs for de-multiplexing the 250MHz signal into a 16 MHz signal[1]. The main part of the processing system consists of memory chips and Field Programmable Gate Arrays (FPGAs), which make the 2-tap filters[6].

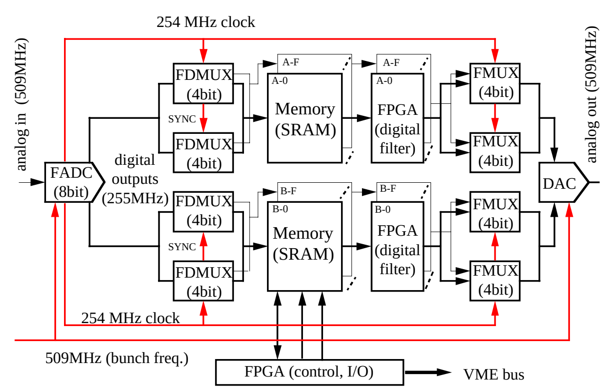

Figure 4: Block diagram of the KEKB signal process board.

The above two examples were designed at each laboratory, since it was less feasible to assemble a system with commercial products. Recently, the feedback systems developed at ELETTRA[13], many commercial products have been used. They use DSPs for the main processing part like the system at SLAC.

3.3 Kicker part

A kicker part accepts the output of the signal processing part and amplifies it to generate a field to kick bunches in the feedback kickers. The key parameters characterizing

[1] Actually this LSI can function with the input rate of 500MHz

a power amplifier are the maximum power and the bandwidth. Additionally, the step response is another important check-point evaluating these amplifiers. At present, a traveling-wave tube type and solid-state type are used in several laboratories.

In the transverse planes, a set of four stripline electrodes is used as a kicker. A TEM wave propagates along these striplines and the electric field is generated around the center of the beampipe. When a horizontal kicker is positioned at a point where the dispersion is non-vanishing, it works not only as a horizontal kicker but also as an effective longitudinal kicker. In fact, longitudinal feedback using this technique is adopted in CESR[14].

There are two important parameters characterizing the kicker: one is the bandwidth and the other is the shunt impedance, which is defined by $V^2/(2P)$, where V is the generated kick voltage and P the power fed to the kicker. By evaluating which parameter between the two is more important, we discern two approaches in designing the longitudinal kicker. The first approach, in which the bandwidth is emphasized, is to create a longitudinal field between two drift-tube-like structures which are longitudinally aligned. It is essentially striplines connected by a half wavelength-delay, along which a TEM wave propagates. This stripline-type of kickers was developed at LBNL[15] and was first installed at ALS. After succesful operation of these kickers at ALS, the same type of kicker has been used at PEP-II.

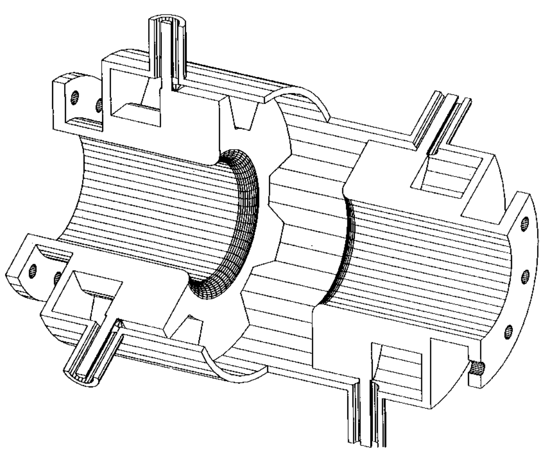

Figure 5: A cut view of the DAFNE longitudinal kicker.

The second approach, in which the shunt impedance was mainly considered, is to make a cavity with an extremely low quality-factor, on the order of 1 or 10. There are several examples of this approach[16][17], but a typical one is that developed at Frascati for the DAFNE storage rings. A cutaway view of this kicker is shown in Fig. 5[18]. The main body of the kicker is a simple pillbox cavity and the usual TM_{010} mode is used to kick the bunches. The problem is how to degrade the quality factor. The method they adopted is to use three ridged waveguides as input-couplers. The outputs are also the same type waveguides. By the wire measurement method, the shunt impedance of this kicker is found to be 700$\sim$800 Ohms with $Q \sim 7$. At present, this longitudinal kicker is used in the multibunch operation of DAFNE.[19] Moreover, this type of kicker are used at KEKB, BESSY II with small modifications.

4 SEVERAL EXAMPLES OF BUNCH FEEDBACK SYSTEMS

4.1 KEKB

At the beginning of Dec. 1998, the commissioning of the KEKB rings started, and simultaneously, the tuning of the feedback components has started. After beam-studies of one to two months, the KEKB commissioning team found that the threshold currents of the multibunch instabilities in both the high-energy (HER) and low-energy rings (LER) were rather low and that the transverse feedback systems were required for stable operation.[20] On the contrary, the KEKB rings are not suffering from serious longitudinal instability. The longitudinal feedback system, which has been installed in the LER, has not yet been used.

One of the serious problems which have been encountered in the KEKB transverse feedback systems is the drift of the closed orbit. At the early stages of the commissioning, the KEKB rings were suffering from relatively low-frequency orbit changes[21]. If the orbit drift is much smaller than the dynamic range of the ADC of the signal processing system, the digital filter can eliminate this DC change. But when the drift is not so small, this DC component must be cancelled with an analog step.

Owning to the Continuous Closed-orbit Correction system (CCC), which was developed by the KEKB optics group, the orbit-drift has been suppressed to the level that the amount of the change is smaller than the dynamic range of the ADC. In addition, we started to use the 2-tap filter which has been not employed because of frequent change of the ring optics.

4.2 ALS/PEP-II

In the early 90s, SLAC-LBNL feedback R+D teams started to develop transverse and longitudinal feedback systems. They set a target of constructing feedback system which can handle 2-ns spacing. In mid-90's, construction of ALS was completed and the feedback systems started operation. Figure 6 shows a block diagram of the ALS longitudinal feedback system. They use the signal processing system we discussed in the last section.

After the ALS, conceptually the same, but extended systems have been commissioned at PEP-II. It is playing an important role in the stable operation of PEP-II[22][23].

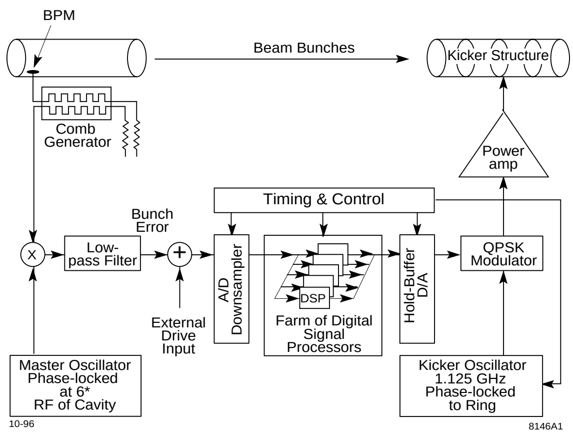

Figure 6: Block diagram of the longitudinal feedback systems at ALS.

5 BEAM DIAGNOSTICS SYSTEM BASED ON DIGITAL FEEDBACK SYSTEM

Up to the last section, we have reviewed the features of the modern digital feedback systems. These systems hold a large amount of bunch-position data within their memory. Particularly, for the longitudinal system, a typical data-size is (turn-numbers for 1/4 synchrotron period)$\times$(# of bunches). Then the signal processing part of these digital feedback systems become a treasure house of clues for investigating beam instabilities.

A traditional tool for analyzing the nature of multibunch instabilities has been a spectrum analyzer. But analysis by this device is less powerful when the bunch filling pattern is not symmetric. Additionally, it is almost useless for observing transient phenomena such as bunch-motions just after start-up of the oscillation.

In contrast with this tool, the feedback system is a wide-band device able to handle transient phenomena with uneven filling patterns of the bunches. At first, the power of such systems are demonstrated by the ALS/PEP-II longitudinal system[24]. Slightly after the SLAC system, the KEK system also completed. Figure 7 shows data taken by the KEK 20Mbytes-memory system. The growth of oscillations is displayed as functions of bunch-ID/mode-ID and the turn number.

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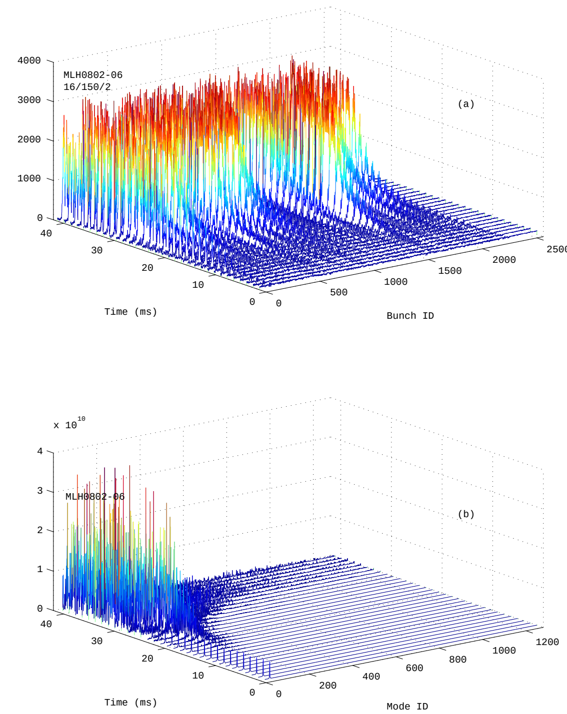

Figure 7: The data taken in LER at KEKB. Horizontal oscillation is growing, just after the feedback is turned off.

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