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S.V. Ivanov

USE OF A DELAY-LINE FILTER IN TRANSVERSE FEEDBACK OF A SYNCHROTRON

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Abstract

Ivanov S.V. Use of a Delay-Line Filter in Transverse Feedback of a Synchrotron: IHEP Preprint 97-64. – Protvino, 1997. – p. 12, figs. 8, tables 1, refs.: 3.

Generalities of how to use a delay-line-based FIR filter inside a transverse feedback of a synchrotron are discussed. A technical solution suitable for modernization of transverse injection-error and coherent-instability damping system of the IHEP U-70 proton synchrotron is proposed.

Аннотация

Иванов С.В. Использование фильтра на линиях задержки в цепи поперечной обратной связи синхротрона: Препринт ИФВЭ 97-64. – Протвино, 1997. – 12 с., 8 рис., 1 табл., библиогр.: 3.

Обсуждаются общие принципы использования КИХ фильтров на линиях задержки в цепи поперечной обратной связи синхротрона. Предложен вариант технического решения для модернизации системы подавления поперечных ошибок инжекции и когерентных неустойчивостей пучка в протонном синхротроне ИФВЭ У-70.

Introduction

The first proposal to use periodic notch filter made of (analog) delay lines inside transverse feedback of a synchrotron — booster NSLS BNL has been reported in [1]. Application of this principle of feedback signal processing looks most attractive in the frames of a DSP technique (linear non-recursive digital FIR filters on delay registers). In this manner, the feedback circuit in question is implemented at synchrotrons PETRA DESY [2] and SPS CERN [3].

This paper serves a dual purpose of reviewing the subject matter, and putting forward a proposal to use delay-line-based filters in course of a feedback circuitry upgrade at the IHEP proton synchrotron U-70.

1. Introductory Notes

Denote generalized azimuth of a synchrotron by Θ, angular velocity of on-momentum particle by ω_0, and time by t. Introduce azimuth $\vartheta = \Theta - \omega_0 t$ in a co-rotating frame.

Assume that the beam describes transverse coherent oscillations along direction y (horizontal, vertical). Let $D(\vartheta, t)$ and $S(\vartheta, t)$ be y-components of beam dipole electric moment and deflecting Lorentz force field strength, respectively. Both can be decomposed into plane waves

$$D(\vartheta, t) = \frac{1}{2\pi} \sum_{k=-\infty}^{\infty} \int_{-\infty}^{\infty} d\Omega\, D_k(\Omega) \exp(ik\vartheta - i\Omega t), \tag{1}$$

$$S(\vartheta, t) = \frac{1}{2\pi} \sum_{k=-\infty}^{\infty} \int_{-\infty}^{\infty} d\Omega\; S_k(\Omega) \exp(ik\vartheta - i\Omega t). \tag{2}$$

Frequency Ω of the Fourier transform is seen in the lab-frame as a side-line of rotation frequency harmonics, $\omega = k\omega_0 + \Omega$.

Electrodynamic properties of vacuum chamber that may result in occurrence of transverse deflecting forces are commonly described in terms of transverse coupling impedance $Z_k(\omega)$ which is defined by

$$S_k(\Omega) = \frac{i\,\beta\omega_0}{2\pi\,R_0}\,Z_k(k\omega_0 + \Omega)\,D_k(\Omega), \qquad [Z_k(\omega)] = \text{Ohm/m}, \tag{3}$$

where β is reduced velocity, R_0 is average radius of the accelerator. Transverse impedance obeys a reflection symmetry $Z_{-k}(-\omega) = -Z_k^*(\omega)$. In the case of a passive element of beam environment, $\mathrm{Re}Z_k(\omega) > 0$ at $\omega > 0$.

Frequency Ω is found as a solution for a stability problem. For an **unbunched** beam, it is

$$\Omega \simeq Q\omega_0, \tag{4}$$

where Q is betatron tune. Wave number k is also an index of unbunched-beam azimuthal eigenmode which is nothing but an isolated plane wave.

For a **bunched** beam,

$$\Omega \simeq Q\omega_0 + m\Omega_s, \tag{5}$$

where $m = 0, \pm1, \pm2, \ldots$ is an index of a bunch head-tail mode, Ω_s is circular frequency of synchrotron oscillations. Azimuthal eigenmodes of a beam made of M identical equidistant bunches are enumerated with index $n = 0, 1, \ldots, M-1$. Each mode is associated with a set of wave numbers $k = n + M\ell$ where ℓ is an integer. Azimuthal mode n is but a beam coherent oscillation with a phase shift $2\pi n/M$ between adjacent bunches.

Magnitude of beam coherent response to external deflecting force can be conveniently characterized by a factor R_T which has a dimension of transverse coupling impedance

$$R_T = -\frac{4\,pc}{eJ_0\langle\beta\rangle} < 0, \qquad [R_T] = \text{Ohm/m} \tag{6}$$

where p is momentum of particles, J_0 is averaged over orbit beam current, c is speed of light, $\langle\beta\rangle$ is average value of amplitude function of accelerator, $\langle\beta\rangle \simeq R_0/Q$.

Interaction of a beam with its environment results in complex coherent tune shift

$$\Delta Q \simeq \frac{i\zeta_a(Q\omega_0)}{\pi R_T}, \tag{7}$$

and instability arises when $\mathrm{Im}\Delta Q > 0$.

Quantity $\zeta_a(\Omega)$ can be referred to as an instability driving impedance for azimuthal mode a. For an **unbunched** beam, it is merely

$$\zeta_a(\Omega) = Z_k(k\omega_0 + \Omega), \qquad a = k. \tag{8}$$

In the case of a **bunched** beam made of M point-like bunches,

$$\zeta_a(\Omega) = \textstyle\sum_{\ell=-\infty}^{\infty} Z_k(k\omega_0 + \Omega)\,\delta_{k,n+M\ell}, \qquad a = n \tag{9}$$

where $\delta_{kk'}$ is Kronecker's delta-symbol.

Eqs. 4, 5 use sign $+Q$. That is, the so called upper side-bands of betatron oscillations are taken into account whose frequencies are $\omega \simeq (k+Q)\omega_0$. Under such a convention, a stable plane wave must have such a frequency $\omega \simeq (k+Q)\omega_0$ that yields $\mathrm{Re}Z_k(\omega) > 0$. For passive components of beam environment, the latter inequality holds true at half-axis $\omega > 0$, and these are the slow waves with phase velocities $0 < \omega/k < \omega_0$ that are prone to instability. (Alternatively, one could have adopted sign $-Q$, lower betatron side-bands with frequencies $\omega \simeq (k-Q)\omega_0$ and stabilizing impedances that obey $\mathrm{Re}Z_k(\omega) < 0$.)

2. Transverse Feedback

2.1. Impedance Imposed by Feedback

Consider a feedback (FB) circuit with a short pick-up PU and a kicker K located at azimuths $\Theta_{\rm PU}$ and $\Theta_{\rm K}$, respectively. Let kicker's position be at a distance $\Delta\Theta_{\rm K-PU} = \Theta_{\rm K}-\Theta_{\rm PU} > 0$ downstream of pick-up, $\Delta\Theta_{\rm K-PU} \leq 2\pi$. Fig. 2.1 sketches the FB schematics.

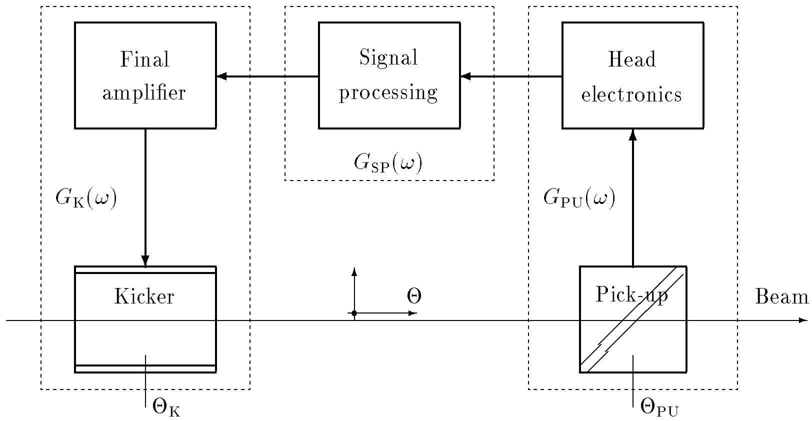

Fig. 1. Transverse FB circuit.

Assume that the FB causes a betatron tune shift with $|\Delta Q| \ll 1$. Then, its effect on beam can be described in terms of a transverse coupling impedance imposed. To find the latter, take a plane wave of beam dipole perturbation $\propto \exp(ik\Theta - i\omega t)$ that propagates along azimuth Θ with amplitude $D \equiv J_0\Delta y/\omega_0$ where Δy is a beam transverse offset. Harmonic signal $J_0\Delta y\,\exp(ik\Theta_{\rm PU} - i\omega t)$ of beam is detected by pick-up, then it is processed by FB circuitry and ultimately drives a localized deflecting field $\propto \delta(\Theta - \Theta_{\rm K})\exp(ik\Theta_{\rm PU} - i\omega t)$ at kicker. On decomposing this field into Fourier series in Θ, one can use Eq. 3 to get

$$Z_k^{(fb)}(\omega) \;=\; -i\,G(\omega)\,\exp\left(-ik\Delta\Theta_{\rm K-PU}\right), \tag{10}$$

$$G \;=\; \frac{(EL)_{\rm K}}{\beta(J_0\Delta y)_{\rm PU}} = \frac{{\rm c}(BL)_{\rm K}}{(J_0\Delta y)_{\rm PU}}. \tag{11}$$

Here, $G(\omega)$ is a transfer function through FB loop measured in Ohm/m. Quantities $(EL)_{\rm K}$ and ${\rm c}\beta(BL)_{\rm K}$ are integrated field strengths of an electric or a magnetic kicker, respectively. Sometimes, the FB circuit is characterized by a gain $\Delta y'/\Delta y$ where $\Delta y' = \Delta(dy/ds)$ is a magnitude of angular correction. In this case, instead of Eq. 11, use can be made of the definition

$$G = \frac{p{\rm c}}{eJ_0}\left(\frac{\Delta y'}{\Delta y}\right). \tag{12}$$

Coupling impedance (Eq. 10) imposed by FB can be inserted into Eqs. 8, 9 together with that of vacuum chamber. Here, it is through this channel that FB circuit performances affect the solutions of a beam stability problem.

Open-loop in-out gain $G(\omega)$ is due to a cascade connection of three circuit sections and their transfer functions: $G_{\rm PU}(\omega)$ of pick-up and head electronics, $G_{\rm SP}(\omega)$ of FB signal processing network, and $G_{\rm K}(\omega)$ of final amplifier and kicker. Therefore,

$$G(\omega) = G_{\rm K}(\omega) \cdot G_{\rm SP}(\omega) \cdot G_{\rm PU}(\omega). \tag{13}$$

Circuit sections $G_{\rm PU}$ are $G_{\rm K}$ analog ones, while $G_{\rm SP}$ can be either analog or digital. To simplify the matters, let us attribute the overall loop gain and time delay of the FB signal to $G_{\rm SP}$, $[G_{\rm SP}] = $ Ohm/m. For the time being, take $G_{\rm K} \cdot G_{\rm PU} \simeq 1$ inside FB bandwidth $|\omega| \lesssim \Delta\omega^{(fb)}$, and consider $G_{\rm SP}$ only which is the core of entire FB.

2.2. FB Circuit with Delay $\leq 2\pi/\omega_0$

This is a standard technical option based on arguments to follow.

In a perfect case of a wide-band FB, one gets

$$G_{\rm SP}(\omega) = \pm G_0 \, \exp\left(i\omega\tau\right), \tag{14}$$

where $G_0 > 0$ is gain, τ is time delay through the FB. A proper sign choice is specified later on.

Time synchronization requirement

$$\tau = \Delta\Theta_{\rm K-PU}/\omega_0 \tag{15}$$

ensures the correction being applied precisely to the beam sample measured.

Setting pick-up to kicker distance in compliance with

$$\Delta\Theta_{\rm K-PU}\, Q = \frac{\pi}{2}\,(2j+1), \qquad \text{where } j \text{ is an integer}, \tag{16}$$

takes into account that, as a matter of fact, it is a beam sample off-set Δy that is measured, the same sample's angular coordinate $\Delta y'$ being subsequently subjected to correction.

Put Eq. 14 and $\omega = (k+Q)\omega_0$ into Eq. 10. Then, use of Eqs. 15, 16 would cancel out complex factor $-i\exp(-ik\Delta\Theta_{\rm K-PU})$ in Eq. 10 and transform it into

$$Z_k^{(fb)}((k+Q)\omega_0) = \pm(-1)^j G_0 = G_0 + i0. \tag{17}$$

The latter equality — a condition for damping of betatron oscillations with $\mathrm{Re}\Delta Q = 0$ — is arrived at with a sign choice in Eq. 14 such as to put it in compliance with a real distance (Eq. 16) between pick-up and kicker.

The FB just mentioned is not free of inherent drawbacks:

First, it essentially relies on Eq.16 that depends on betatron tune Q adopted. Often, ring magnetic lattice itself does not allow for installing pick-up and kicker in accord with Eq. 16 even for a nominal operating point of accelerator. To this end, a "virtual" pick-up and/or kicker concept is applied to, which is based on a weighted summation of signals from a pair of devices.

Second, dedicated efforts must be undertaken to suppress an input signal from a steady-state beam rotating around a (distorted) closed orbit. Here, various solutions are possible. For example, to adjust gains of signals from plates of a differential pick-up to make its electrical center follow a closed orbit position. Sometimes, an average value of signals picked up at a few subsequent turns is found and subtracted from the current reading.

However, there exists a technical solution of FB circuit which resolves the problems just mentioned in a more straightforward way.

2.3. FB Circuit with Delay $\geq 2\pi/\omega_s$

Let us withdraw a requirement to obey Eq. 16. Suppose that $G_{\rm SP}(\omega)$ employs a few lines delaying signals by an integer number of turns plus a common extra delay by the same (Eq. 15) time of flight

$$\begin{aligned} G_{\rm SP}(\omega) &= G_0 \, \exp\left(i\omega\tau\right) \textstyle\sum_{q=0}^{H} w_q \, \exp\left(i\omega \, 2\pi q/\omega_0\right), \\ \tau &= \Delta\Theta_{\rm K-PU}/\omega_0 \end{aligned} \tag{18}$$

where $G_0 > 0$ is gain, w_q are real summation weights, $H+1$ is number of delay lines. Eq. 18 can be treated as a transfer function of a (non-recursive) filter with a finite time impulse response, the so called FIR filter.

Let $G_{\rm SP}(\omega)$ be a periodical notch filter

$$G_{\rm SP}(k\omega_0) = 0 \qquad \text{wherefrom} \qquad \textstyle\sum_{q=0}^{H} w_q = 0. \tag{19}$$

This would reject a signal emerging from a steady-state beam rotating around equilibrium orbit that does not pass through electrical center of pick-up. (Signals at frequencies $\omega = k\omega_0$ with $k \neq 0$ are driven by a beam with unequal or missing bunches.)

Simultaneously, let one demand that

$$G_{\rm SP}((k+Q)\omega_0) = i\, G_0 \, \exp\left(ik\Delta\Theta_{\rm K-PU} + i\varphi\right) \tag{20}$$

so as to compensate for a complex factor $-i\exp(-ik\Delta\Theta_{\rm K-PU})$ in Eq. 10 at betatron side-bands. Then, Eq. 10 would acquire the form

$$Z_k^{(fb)}((k+Q)\omega_0) = G_0 \exp(i\varphi). \tag{21}$$

In particular, on adopting $\varphi = 0$, one gets damping of betatron oscillations with ${\rm Re}\Delta Q = 0$ similar to that of the earlier case of Eq. 17.

To fulfill Eqs. 19, 20, it is necessary and sufficient to use three delay lines ($q = 0, 1, 2$). The weight coefficients thus required are

$$w_0 = -\frac{\sin\left((3\pi + \Delta\Theta_{\rm K-PU})Q - \varphi\right)}{2\,\sin\pi Q\,\sin 2\pi Q}, \tag{22}$$

$$w_1 = +\frac{\sin\left((2\pi + \Delta\Theta_{\rm K-PU})Q - \varphi\right)}{2\,\sin^2\pi Q}, \tag{23}$$

$$w_2 = -\frac{\sin\left((\;\pi + \Delta\Theta_{\rm K-PU})Q - \varphi\right)}{2\,\sin\pi Q\,\sin 2\pi Q}. \tag{24}$$

As can be easily seen, the FB at issue fails to operate under integer and half-integer Q. Indeed, in such a case, pick-up reads at each turn precisely in-phase or out-of-phase signals due to coherent off-set of a beam sample. Their quadrature-phase content is lost completely. Weighted summation of these signals is no longer able to recover phase relationships required by Eq. 20. All the more, under integer Q, one cannot apply to frequency discrimination between signals due to closed orbit errors and those due to beam coherent motion: arguments of l.h.s. of Eqs. 19, 20 coincide which makes these equations incompatible.

Eqs. 22–24 contain $\Delta\Theta_{\mathrm{K-PU}}$ as a free parameter. In principle, it allows one to discard one of the delay lines (by q turns) by requiring $w_q = 0$ for $q = 0, 1$ or 2. Suffice it to take the pick-up to kicker distance in accord with

$$((3-q)\pi + \Delta\Theta_{\mathrm{K-PU}})\,Q - \varphi = \pi j, \qquad \text{where } j \text{ is an integer.} \tag{25}$$

However, in this case we essentially return to the situation of Eq. 16 with the same inherent drawbacks (a necessity to use "virtual" pick-ups and kickers). In general, use of two delay lines only allows one to satisfy any pair of three requirements to follow: (a) arbitrary $\Delta\Theta_{\mathrm{K-PU}}$, (b) $G_{\mathrm{SP}}(k\omega_0) = 0$ and (c) $\mathrm{Re}\Delta Q = 0$.

FB system in [2] also uses a FIR filter on three delay lines. Still, the set of weight coefficients adopted there is different from that of Eqs. 22–24: $w_0 = -w_2$ and $\sum_{q=0}^{2} w_q = w_1 \neq 0$. This option obviously under-uses all the possibilities opened by the FIR filter with $H = 2$.

To conclude the section, consider a particular case of a narrow-band FB destined to damp a single azimuthal harmonic $k = -([Q]+1)$ where $[Q]$ is the integer part of betatron tune. This harmonic is most strongly excited by a resistive vacuum chamber. In this case, the FIR filter of Eq. 18 can be used as a variable phase-shifter. Indeed, phase φ of circuit section G_{SP} (Eq. 20) can be readily controlled with a proper choice of summation weights $w_q = w_q(\varphi)$ from Eq. 22–24 so as to compensate for a variation of phase in section $G_{\mathrm{K}} \cdot G_{\mathrm{PU}}$ during acceleration

$$\varphi + \arg\Big(G_{\mathrm{K}}\big((\{Q\}-1)\omega_0\big) \cdot G_{\mathrm{PU}}\big((\{Q\}-1)\omega_0\big)\Big) = 0 \tag{26}$$

where $\{Q\}$ is the fractional part of betatron tune. (Naturally, this phase-shifter, being also the notch FIR filter (Eq. 18), would also reject a DC content of a signal from pick-up.)

3. FB systems for U-70

Let us estimate feasible technical contours of transverse FB systems on delay lines for the U-70 proton synchrotron. Its relevant parameters are specified in Table 1, the lower part of which corresponding to a final stage of U-70 upgrade program.

Table 1. U-70 Data List

Injection energy (kinetic)	1.32	GeV
Top energy (kinetic)	67.0	GeV
Average radius of orbit, R_0	236.14	m
RF harmonic number, h	30	
Radio-frequency, $\omega_{\rm RF}/2\pi$	5.512 – 6.061	MHz
Number of bunches, M	$(\le)30$	
Rotation frequency, $\omega_0/2\pi$	183.7 – 202.0	kHz
Betatron tune, Q	9.7 – 9.9	
Number of particles, N	$5.0{\cdot}10^{13}$ p.p.p.	
Beam average current, J_0	1.47 – 1.62	A
Vacuum chamber dimensions (ellipse)		
horizontal semi-axis	10.0	cm
vertical semi-axis	5.0	cm
Vacuum chamber wall thickness	3.0	mm
Specific resistance of walls		
(stainless steel), ρ	$70\cdot 10^{-8}$	Ohm·m

3.1. Wide-Band Feedback

Let us proceed from the equipment already existing — electrostatic pick-ups located in straight sections # 107 and # 111, and magnetic kicker housed in straight section # 90 of U-70. For definiteness, take pick-up from straight section # 107. Then, $\Delta\Theta_{\rm K-PU}\simeq 2\pi\cdot 103/120$. Fig. 2 shows summation weights w_q ($\varphi=0$) versus operating point of U-70.

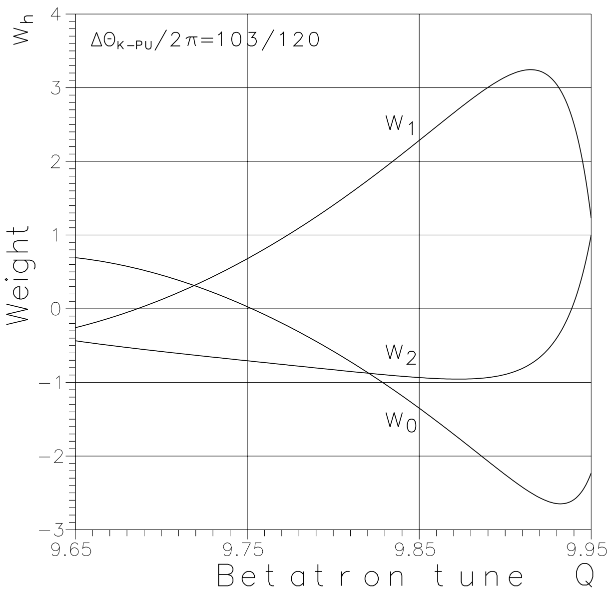

Fig. 2. Summation weights (wide-band FB).

Demand that the FB circuit should affect all $M=30$ azimuthal modes n available. Then, its bandwidth must occupy a range exceeding $0.5\max\omega_{\rm RF}\simeq 2\pi\times 3.0$ MHz. Assume that it stretches from $2\min\omega_0\simeq 2\pi\times 0.4$ MHz till $(M/2+2)\max\omega_0\simeq 2\pi\times 3.4$ MHz.

Let us now withdraw the assumption $G_{\rm K}\cdot G_{\rm PU}\simeq 1$ used earlier. Let $G_{\rm PU}(\omega)$ be a cascade connection of a differentiator and a 3-rd order Butterworth filter,

$$G_{\rm PU}(\omega)=\frac{-i\omega}{\Delta\omega_{\rm PU}-i\omega}\times\frac{\Delta\omega_{\rm B}^3}{(\Delta\omega_{\rm B}^2-i\omega\Delta\omega_{\rm B}-\omega^2)(\Delta\omega_{\rm B}-i\omega)} \tag{27}$$

where lower and higher cut-off frequencies are set to $\Delta\omega_{\rm PU} = 2\pi \times 0.2$ MHz and $\Delta\omega_{\rm B} = 2\pi \times 3.54$ MHz (a middle point of unused interval between harmonics $|k + [Q]| = M/2 + 2$ and $M/2 + 3$). Here, low-pass filter is employed to suppress the unused high-frequency content of a signal from pick-up before its analog-to-digital conversion. Let $G_{\rm K}(\omega)$ be an integrating circuit

$$G_{\rm K}(\omega) = \frac{\Delta\omega_{\rm K}}{\Delta\omega_{\rm K} - i\omega} \tag{28}$$

whose cut-off frequency $\Delta\omega_{\rm K} = 2\pi \times 3.54$ MHz coincides with that of Eq. 27.

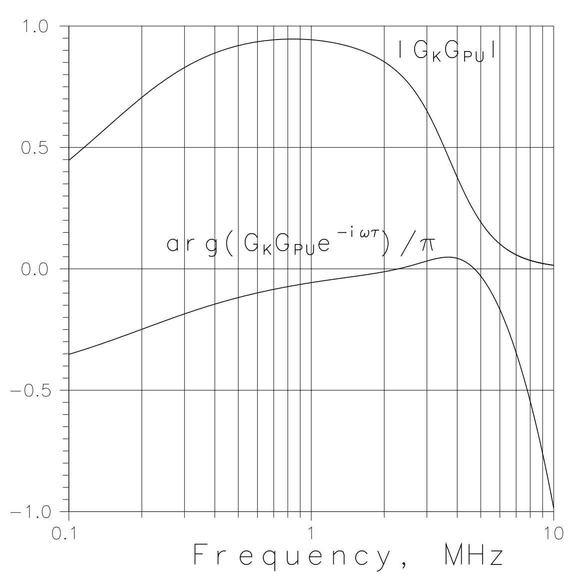

Fig. 3. Analog sections of wide-band FB.

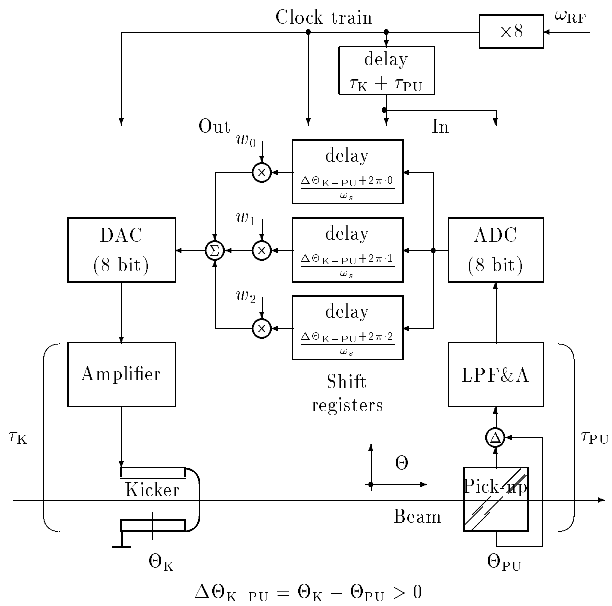

Fig. 4. Block diagram of FB system for U-70.

Let us attribute a group delay equal to 132 ns (without cable communications) to a cascade connection $G_{\rm K} \cdot G_{\rm PU}$. It can be compensated at the expense of an appropriate decrease of delay in FB signal processing section $G_{\rm SP}$ (i.e., by introducing the so called "negative delay"). As a result, $G_{\rm K} \cdot G_{\rm PU}$ acquires an acceptable phase-frequency response inside the operating bandwidth shown in Fig. 3.

The applying to a digital FB signal processing ensures the simplest handling of problems caused by varying through the cycle of U-70 rotation frequency ($\Delta\omega_0 \simeq 2\pi \times 18.3$ kHz) and variable delay lines ($\Delta\tau \simeq 493$ ns). The block diagram of transverse FB for U-70 is shown in Fig. 4.

Clock frequency of digital electronics is derived from the 8-th harmonic of the current radio-frequency (1 turn = 240 clock periods). It ensures at least 7 samples per period of the highest beam harmonic with frequency ~ 6 MHz that occurs inside FB bandwidth (at -20 dB level). The reproduction accuracy of this harmonic is better than $\sim$9%. Sampling frequency of ADC and DAC ranges within 44.2–48.5 MHz through the cycle.

FIR filter (Eq. 18) may be based on three shift registers (FIFO) whose outputs are summed with weights $w_q = w_h(Q)$ that depend upon the position of an operating point through the acceleration cycle. To compensate for pure delay $\tau_K + \tau_{PU}$ in analog section $G_K \cdot G_{PU}$ plus cable communications, the input clock train (ADC and writing into shift registers) is delayed w.r.t. output clock frequency (reading and DAC) by the same time $\tau_K + \tau_{PU}$.

Fig. 5 shows betatron tune shift $\Delta Q^{(fb)}$ (in units of $G_0/(\pi|R_T|)$) imposed by FB circuit for various azimuthal modes n.

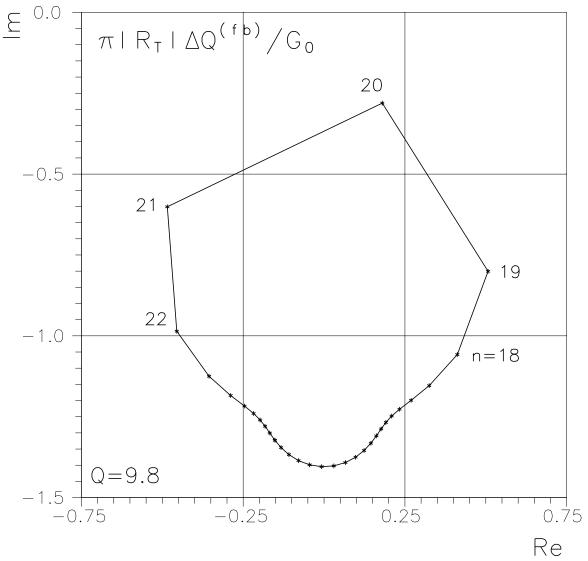

Fig. 5. Betatron tune shift (wide-band FB).

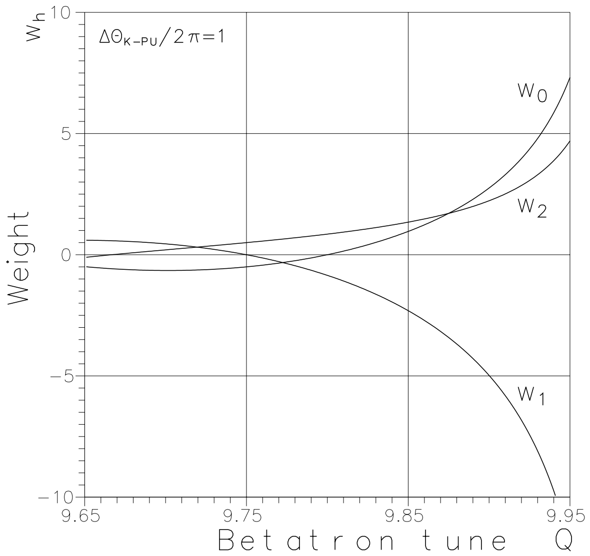

Fig. 6. Summation weights (narrow-band FB).

Injection flat-bottom with $Q = 9.8$ is considered. All the azimuthal modes n are damped ($\mathrm{Im}\Delta Q^{(fb)} < 0$) but, due to non-flatness of phase-frequency response of $G_K \cdot G_{PU}$ section, one fails to get $\mathrm{Re}\Delta Q^{(fb)} \simeq 0$.

A resistive vacuum chamber destabilizes 15 azimuthal modes $n = 6$–20. This FB circuit is not aimed at achieving strong damping of resistive-wall instability of the most dangerous modes $n = 19, 20$ whose wave-number spectrum contains $k = -11, -10$ with low frequency lines $(k + Q)\omega_0 \lesssim 0$. (To this end, a narrow-band FB discussed in the following Section is to be used.) For the remaining modes $n = 6$–18, skin depth is less than wall thickness, and a "thick-wall" approximation holds when resistive wall impedance is $Z_k(\omega) \propto -i/\sqrt{-i\omega}$. To damp vertical resistive wall instability of modes $n = 6$–18, gain $G_0 \gtrsim 0.35$ MOhm/m is sufficient. In a horizontal direction, due to vacuum chamber ellipticity, G_0 may be decreased by a factor of 1.83. (In U-70, such a decrease occurs by itself because of a decreased sensitivity of radial pick-ups, gain of FB electronics being kept intact.)

The integrated field $c(BL)_K$ of U-70 magnetic kicker ranges within ± 10.7 kV (its constant $B/I = 0.065 \cdot 10^{-4}$ T/A, amplitude of driving current $I = 5$ A and length $L = 1.1$ m). Herefrom it follows that at $G_0 \simeq 0.35$ MOhm/m and beam intensity $N = 5.0 \cdot 10^{13}$ p.p.p. a linear dynamical range of the FB circuit would be as high as

$\Delta y \simeq \pm(2.1\text{–}1.9)$ cm in vertical and $\Delta y \simeq \pm(3.8\text{–}3.5)$ cm in horizontal directions. These define the magnitudes of transverse injection errors that are treated by FB circuit in a linear regime.

3.2. Narrow-Band Feedback

This FB circuit can use the same block diagram that is shown in Fig. 4. Again, let proceed from the equipment already available — electrostatic pick-up and kicker located in straight section #2 of U-70. Then, $\Delta\Theta_{\rm K-PU} \simeq 2\pi$. Fig. 6 shows summation weights w_q ($\varphi = 0$) versus the operating point of U-70.

Let this FB circuit be handling, mostly, modes $n = 18$–22 whose wave number spectrum includes $k = -(12$–$8)$ with low frequency lines $(k+Q)\omega_0 \simeq 0$. Then, the FB must be a low-pass one, with bandwidth $\gtrsim 2\max\omega_0 \simeq 2\pi \times 0.4$ MHz.

Let analog section $G_{\rm K}\cdot G_{\rm PU}$ of the FB circuit be given by the same Eqs. 27, 28 where lower and higher cut-off frequencies are $\Delta\omega_{\rm PU} = 2\pi\times 1.0$ kHz and $\Delta\omega_{\rm B}, \Delta\omega_{\rm K} = 2\pi \times 0.5$ MHz.

Let us attribute a group delay equal to 976 ns (without cable communications) to a cascade connection $G_{\rm K}\cdot G_{\rm PU}$. Having compensated for it by introducing a "negative delay", one gets phase-frequency response shown in Fig. 7.

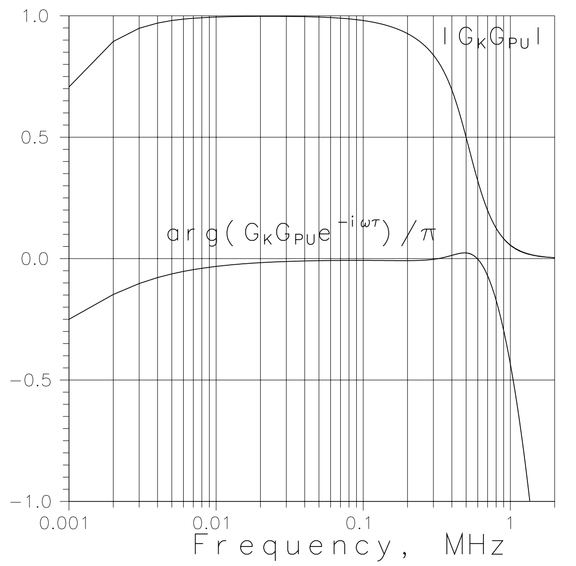

Fig. 7. Analog sections of narrow-band FB.

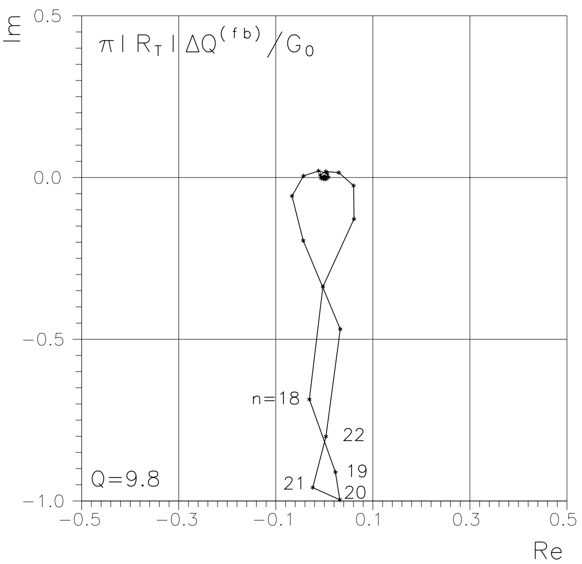

Fig. 8. Betatron tune shift (narrow-band FB).

Clock frequency of digital electronics is derived from the 1-st harmonic of the current radio-frequency (1 turn = 30 clock periods). It ensures, at least, 6 samples per period of the highest beam harmonic with frequency $\sim$ 0.85 MHz that occurs inside the FB bandwidth (at -20 dB level). The reproduction accuracy of this harmonic is better than $\sim$12%. Sampling frequency of ADC and DAC ranges within 5.5–6.1 MHz through the cycle.

Fig. 8 shows betatron tune shift $\Delta Q^{(fb)}$ imposed by the narrow-band FB circuit for various azimuthal modes n. Injection flat-bottom with $Q = 9.8$ is considered. The FB circuit damps modes $n = 15$–25. For modes $n = 17$–23 occurring in the center of bandwidth, $\mathrm{Re}\Delta Q^{(fb)} \simeq 0$. A few azimuthal modes occurring near the bandwidth cut-off are weakly destabilized by the FB itself. However, this effect will be overridden either by the above wide-band FB or by nonlinearity of betatron motion.

A resistive vacuum chamber strongly destabilizes azimuthal modes $n = 19, 20$. For these, skin depth is equal or a bit less than the vacuum chamber wall thickness. Therefore, we take the most stringent of requirements imposed within the approximations of either "thick" walls whose resistive wall impedance is $Z_k(\omega) \propto -i/\sqrt{-i\omega}$ or "thin" walls with $Z_k(\omega) \propto 1/\omega$. To damp vertical resistive wall instability of modes $n = 19, 20$, gain $G_0 \gtrsim 1.1$–2.1 MOhm/m is sufficient (at $Q = 9.7$–9.9, respectively). In the horizontal direction, G_0 can be decreased by a factor of 1.83.

The integrated field $(EL)_{\mathrm{K}}$ of U-70 electrostatic kicker ranges within ± 35.0 kV (its voltage amplitude $V = 3.5$ kV, the gap between plates $d = 0.1$ m and their length $L = 1.0$ m). Therefore, for $G_0 \simeq 2.1$ MOhm/m and intensity $N = 5.0 \cdot 10^{13}$ p.p.p., a linear dynamical range of the FB circuit would be as high as $\Delta y \simeq \pm(1.2$–$1.0)$ cm in vertical and $\Delta y \simeq \pm(2.3$–$1.9)$ cm in horizontal directions.

Conclusion

A technical solution of transverse feedback systems for U-70 proton synchrotron is proposed. It implies the use of the equipment already installed — pick-ups, kickers and power amplifiers. At a low level, a feedback signal is to be processed digitally with non-recursive FIR filters on three delay registers whose clock frequency is derived from a harmonic of acceleration frequency. In either direction (horizontal, vertical), only one pick-up and one kicker are employed. A distance between them may be rather arbitrary. A signal due to steady-state beam rotating around a (distorted) closed orbit is rejected by notches in FIR filter response. It alleviates the problem of a precise adjustment of electrical center of pick-up.

The proposal can be realized in the frames of U-70 upgrade program.

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