DIGITAL DELAY-LINE PERIODIC FIR FILTER LAYOUT OF TRANSVERSE FEEDBACK IN THE U70

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Abstract

A novel architecture of the wide-band transverse feedback system was successfully beam-tested in the U70 proton synchrotron of IHEP-Protvino. It employs a finite-time impulse response (FIR) non-recursive filter layout based on 3 (or 4, optionally) variable (–10%) multi-turn digital delay lines. Apart of using these natural-to-DSP components, the configuration involved has, at least, two operational advantages: (1) A single beam-pickup layout plus acceptability of an arbitrary betatron phase advance between pickup and kicker. (2) A straightforward rejection of hampering DC and higher rotation frequency harmonic signals from beam position raw readouts. The latter occurs due to a periodic notch nature inherent in the amplitude-frequency in-out open-loop feedback transfer function. The paper reports on technical solutions implemented, problem-oriented R&D, and beam observations.

PREHISTORY

The inventory of transverse beam feedbacks available in the U70 is outlined in Ref. [1].

Layout of the existing wide-band feedback is plotted in Fig. 1. Its two pickups (PU) are located in straight sections (SS) #107 and #111. In the U70, azimuth Θ of SS#n is $2\pi n/120$. A properly weighted sum of beam position readouts produces a virtual pickup located 33 (an odd number) quarter betatron wavelengths upstream of the fast EM kicker (deflector) K in SS#90. A variable (–10% ca) delay line matches open-loop delay rime τ to beam time-of-flight between pickups and kicker.

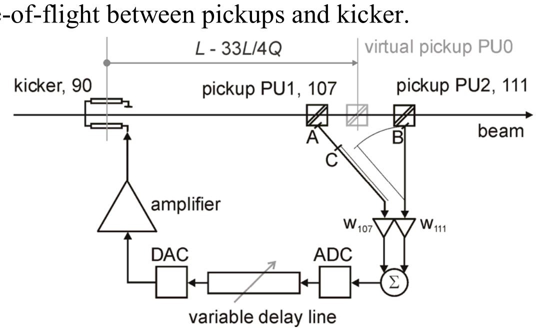

Figure 1: Layout of the existing wide-band feedback.

Suppression of closed-orbit offset signal at $\omega = k\omega_0$, with DC ($k = 0$) included, is accomplished via a variable electrical center of a pickup biased with balance amplifiers. Here, ω_0 is circular beam rotation frequency, integer $k = 0, \pm1, \pm2, \ldots$ is rotation harmonic number.

A single-delay-line layout of Fig. 1 is inherited from the earlier, all-analog implementation of the circuit. Indeed, in the analog world, a 5–20 μs variable delay line is by itself a sufficiently intricate device to preclude any use of a multiple number of them.

To be on the safe side in running the U70 and get experience with the DSP techniques, we have first converted the proven layout of Fig. 1 to a fraction-of-turn digital 1-delay-line version. The outcome is reported in Ref. [1].

In an attempt to better suppress (reject) the persisting closed-orbit offset signal at $\omega = k\omega_0$, a supplementary option using a one-tap periodical (with a period ω_0) digital notch FIR filter in the feedback path was also tested.

Thus, de facto, the U70 has got a digital transverse feedback employing the key techniques of (1) weighted summation of beam signals, (2) two digital delay lines (delays $\tau < 2\pi/\omega_0$ and $\tau + 2\pi/\omega_0$).

Next self-suggesting step was to arrange a more straightforward and promising single-pickup option with 3 (or 4, optionally) variable delay lines shown in Fig. 2.

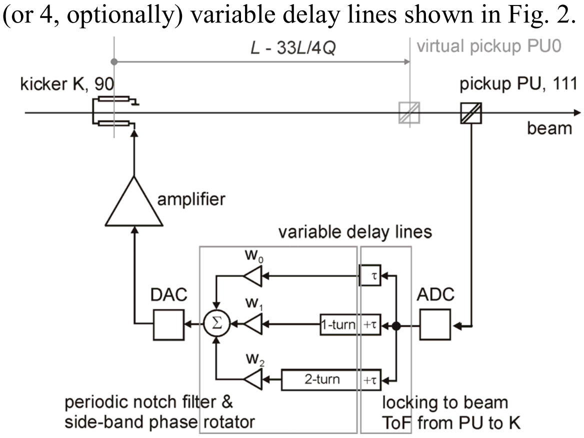

Figure 2: Layout of the new wide-band digital feedback (here, with 3 delay lines).

FIR FILTER LAYOUT

This topology was put forward in Refs. [2, 3]. Its attractive features are:

1. Use of natural-to-DSP circuits, esp., variable delay lines realized, say, as FIFO shift registers clocked by the higher (16^{th}) harmonic of (the U70) acceleration frequency ($\omega_{RF}/2\pi = 5.516$–6.062 MHz).
2. A single beam-pickup layout that saves a room on the orbit.
3. An arbitrary betatron phase advance between pickup and kicker.
4. A natural built-in rejection of (unwanted) steady-state DC and higher rotation frequency harmonic signals present in raw beam position monitor readouts.

The latter occurs due to in-out open-loop feedback transfer function that is synthesized as a periodic notch filter.

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Following the approach of Refs. [1–3], effect of the feedback on beam is treated in terms of a transverse coupling impedance $Z_k^{(FB)}(\omega)$ imposed by the circuit,

$$Z_k^{(FB)}(\omega) = -iG(\omega)\exp(-ik\Delta\Theta_{K-PU}) \qquad (1)$$

where $G(\omega)$ is in-out transfer function of electronics in the open feedback loop, reduced to units of Ohm/m; distance between PU and K (both are short) is $\Delta\Theta_{K-PU} = \Theta_K - \Theta_{PU}$.

On putting aside finite bandwidths of PU, power amplifier and K sections, one gets for the layout of Fig. 2

$$G(\omega) = G_0 \exp(i\omega\tau)\sum_{h=0}^{H} w_h \exp(i\omega 2\pi h/\omega_0) \qquad (2)$$

where a purely real $G_0 > 0$ is feedback gain, τ is delay time of signal processing, w_h are real summation weights, $H + 1$ is the number of delay lines employed (3 or 4). Time τ is set equal to beam time-of-flight from PU to K,

$$\tau = \Delta\Theta_{K-PU}/\omega_0 < 2\pi/\omega_0 \,, \qquad (3)$$

that is the minimal (fraction-of-turn) delay in the system.

The $\exp(-i\omega t)$ and upper betatron side-band conventions are adopted with frequency line series $\omega \cong (k + Q)\omega_0$ where Q is betatron tune (about 9.8–9.9 in the U70).

Then, to impose a purely imaginary (damping) coherent tune shift one has to adjust the feedback to obtain

$$Z_k^{(FB)}(\omega) = G_0 + i0 \quad \text{at} \quad \omega = (k+Q)\omega_0 \,. \qquad (4)$$

Still more, to get the 1st order periodic notches, one sets

$$G(\omega) = 0 \quad \text{at} \quad \omega = k\omega_0 \qquad (5)$$

that requires $H = 2$, or 3 delay lines (FIR-3 filter, Fig. 2).

To widen the rejection stop bands, the 2nd order notches might be foreseen by putting an additional constraint

$$dG(\omega)/d\omega = 0 \quad \text{at} \quad \omega = k\omega_0 \qquad (6)$$

that now requires $H = 3$, or 4 delay lines (FIR-4 filter).

Equations 4, 5 are solved for a 3-delay-line option with

$$w_0 = -\frac{\sin((3\pi + \Delta\Theta_{K-PU})Q)}{2\sin\pi Q \sin 2\pi Q}\,, \qquad (7)$$

$$w_1 = +\frac{\sin((2\pi + \Delta\Theta_{K-PU})Q)}{2\sin^2 \pi Q}\,, \qquad (8)$$

$$w_2 = -\frac{\sin((\pi + \Delta\Theta_{K-PU})Q)}{2\sin\pi Q \sin 2\pi Q}\,. \qquad (9)$$

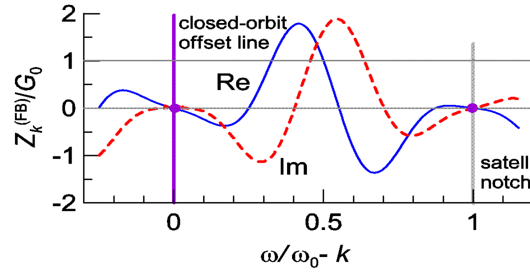
Weights for a 4-delay-line option are given in Ref. [3].

In the U70, $\Delta\Theta_{K-PU} = 2\pi\cdot 99/120$. Consider, for definiteness, a base-line (central) betatron tune $Q_0 = 9¾$. The resultant weight coefficients $w_h(Q_0)$ are listed in Table 1.

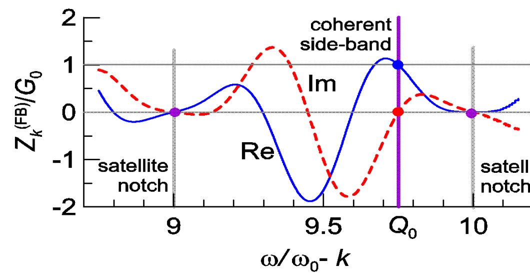
Table 1: Summation weights for FIR filters

FIR-	w_0	w_1	w_2	w_3	Σw_h
3	0.617	–0.963	0.346	0	0
4	0.481	–0.827	0.210	0.136	0

Re and Im parts of $Z_k^{(FB)}(\omega)$ are plotted in Fig. 3. Plots are odd (Re) or even (Im) about the abscissa zero due to reflection symmetry $Z_{-k}(-\omega) = -Z_k(\omega)^*$ of any transverse coupling impedance. Notches in amplitude transfer are 0.10 or 0.13ω_0 wide (FW@G_0/10) for 3 or 4 delays, resp.



Vicinity of the fundamental notch at $\omega = k\omega_0$, Eq. 5.



Vicinity of line $\omega = k\omega_0 + Q$ due to coherent motion, Eq. 4.

Figure 3: Transverse coupling impedance imposed by feedback, a 3-dealay-line option. For a given k, beam probes impedance only in 2 frequency domains shown.

Given fixed weights $w_h(Q_0)$, the feedback will keep on damping in a certain range of tunes Q around the baseline value Q_0. Safety margins are listed in Table 2, where phase $\varphi = 0$ is ascribed to perfect damping (purely imaginary coherent tune shift) at $Q = Q_0$; $\varphi = \pm\pi/2$ stand for a loss of damping, while range $|\varphi| \le \pi/4$ corresponds to the operational data set. Even the unattended system that is not resetting $w_h = w_h(Q)$ in response to $Q \ne Q_0$ is well robust with respect to a variation of the working point.

Table 2: Phase safety margins in Q near Q_0

FIR-	$-\pi/2$	$-\pi/4$	0	$+\pi/4$	$+\pi/2$
3	9.60	9.67	9.75	9.83	10.0
4	9.61	9.68	9.75	9.82	9.88

We have tried but found no practical reasons to employ a 4-delay-line option in the **digital** feedback in question.

Indeed, on the one hand, the last row of Table 2 shows that due to a widened satellite 2nd order notch, the FIR-4 feedback gets a narrower safety margin in the tune offset from Q_0 towards the closest integer $Q = 10$.

On the other hand, the 3 digital delays clocked by a higher harmonic of the RF produce a periodic 1st order notch FIR-3 filter whose stop band zeros by default perfectly follow the rotation harmonics $k\omega_0$ to be rejected. In the final analysis, the same source (the master oscillator and RF) governs the notches and interferences they reject. There is no need to widen the stop bands altogether.

HARDWARE

Analog part of the system is specified in Ref. [1].

Digital part employs COTS digital processing board XDSP-3PCM [http://www.setdsp.ru/] equipped with the

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Xilinx FPGA matrix, 2 ADC (12 bit), 2 DAC (14 bit) and plugged into a PCI slot of an industrial PC iROBO-2000.

Sampling is performed at the 16th harmonic of RF frequency (use of the 8th harmonic invokes under-sampling). Since RF harmonic number in the U70 is 30, the one-turn record length $N = 30 \cdot 16 = 480$ samples. Sampling period Δt is around 10 ns. The delay lines are FIFO shift registers. The fraction-of-turn delay τ is factored out of parallel branches shown in Fig. 2 and is a common variable-length register, while all the multi-turn delays (2 or 3) being the fixed-length devices. The latter constitute a "periodic notch filter and side band phase rotator" network whose optimized topology adopted is shown in Fig. 4.

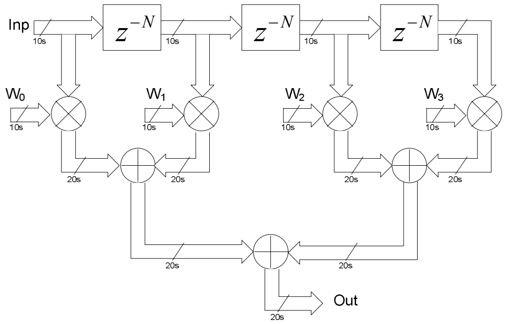


Figure 4: Periodic notch filter and side band phase rotator. z^{-N} is a one-turn delay in the z-transform notation.

Mathematics of the digital processing is executed with truncated 10-bit variables to save resources. Intrinsic in-out delay over the entire DSP section is $10\Delta t$ (100 ns ca).

BEAM OBSERVATIONS

Figures 5 show results of setting variable-length register to lock signal-processing delay τ to beam time-of-flight from pickup PU#111 to kicker K#90, Eq. 3. Top trace is a control signal from the K#90 caused by the earlier bunch traversal through PU#111. Central trace is the same bunch seen with a half of the service PU#90 close to K#90. The correction is applied to the measured beam sample with a time mismatch of about $\pm\Delta t/2$ (±5 ns).

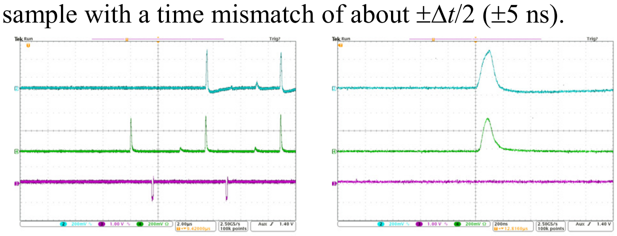


Figure 5: Tuning a fraction-of-turn delay τ.

Operation of the notch filter and side band phase rotator is illustrated by Figs. 6. Raw beam readouts from PU#111 have an unsuppressed DC offset. It is safely eliminated with filtering. In Fig. 6 (left) phase of residual slow coherent signal is rotated by π, intentionally. In Fig. 6 (right) the phase rotation is reduced to $\pi/2$ which allows to convert beam displacement AC signal acquired by PU#111 into beam trace slope correction forced by K#90.

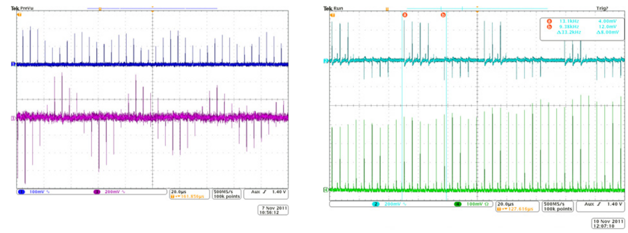
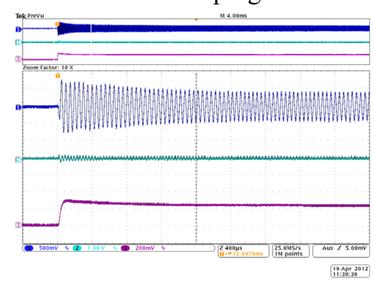
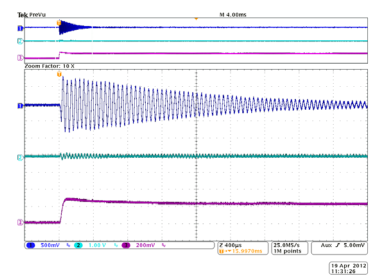


Figure 6: Operation of the notch filter and side band phase rotator with beam signals.

Figure 7 shows effect of closing the 3-delay-line beam feedback at flat-bottom in a linear (proportional) mode. Zoom scan width is 4 ms. Damping time is about 2 ms.



Feedback OFF, a natural decay due to phase-plane mixing



Feedback ON, a forced decay

Figure 7: Damping of radial oscillations at injection (upper trace). Lower trace is beam intensity (DCCT).

CONCLUSION

The novel digital wide-band transverse (horizontal and vertical) beam feedback system was successfully beam-tested in the U70 proton synchrotron during machine runs 2011-2, 2012-1. It was found transparent for tuning and effective in managing the beam.

The most attractive features of the system are (1) an integrated all-in-one handling of steady-state (rejection) and coherent (damping) beam signals, and (2) a single-pickup configuration with an arbitrary betatron phase advance between pickup and kicker allowed.

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