Experiment of RF Feedback using an improved Parallel Comb-Filter

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Abstract

An RF feedback system using a parallel comb-filter has been developed in order to cope with longitudinal coupled-bunch instabilities driven by the accelerating mode of significantly detuned RF cavities. It can reduce the effective cavity impedance at the synchrotron sidebands responsible for the instabilities. This paper describes the experimental results of the RF feedback, which included an improved parallel comb-filter and a low-power test cavity. The real part of the cavity impedance was reduced by 36 dB at maximum over the 7 synchrotron sidebands, 100 kHz apart from each other. The experiment did not include a klystron which presents a frequency-dependent group delay. However, even if a klystron is included, a high loop gain is expected because the parallel comb-filter enables us to precisely adjust the phase at each sideband frequency.

1 INTRODUCTION

In the high beam current machines, such as KEKB [1], the accelerating mode of heavily detuned RF cavities gives rise to very severe longitudinal coupled-bunch instabilities. One way to solve this problem is to use an RF feedback system which can reduce the cavity impedance seen by the beam. We are developing an RF feedback system using a parallel comb-filter, an array of resonators, each of which is tuned at the synchrotron upper sideband of the revolution harmonics. The phase shift of each sideband frequency can be adjusted properly even if a frequency-dependent group delay caused by a klystron and cavities is present around the loop.

In the previous experiment [2], we used a prototype parallel comb-filter which was comprised of five individual LC band-pass filters. Each filter had 2 kHz 3 dB-bandwidth and was arranged with 100 kHz intervals [3]. The RF feedback through a klystron and a choke-mode cavity reduced the real part of the cavity impedance by 16 dB to 24 dB at the five synchrotron sidebands. However, due to insufficient loop gain, the growth time of the two modes ($n = -2, -3$) was still faster than 10 ms, the expected damping time of the longitudinal bunch-by-bunch feedback system [1]. Two higher modes ($n = -6, -7$) were not treated then because of the limitations of available comb-filter channels.

2 REQUIREMENTS

If the normal conducting cavity with no energy storage cell is employed in the KEKB low energy ring (LER), the growth time of the first seven coupled-bunch modes ($n = -1$ to -7) is faster than the damping time of the longitudinal bunch-by-bunch feedback system. To damp all of these modes, at least seven comb-filter channels are required. The loop gain must be increased up to 35 dB to damp the most severe mode ($n = -2$). The loop gain was estimated for several values of filter bandwidth. Table 1 shows the relation between the bandwidth of the filter and the estimated maximum loop gain with a 0° phase margin and with a 45° phase margin over a 1 MHz bandwidth. As this table indicates, the bandwidth of the filter needs to be less than 1 kHz to obtain the required loop gain. The center frequency of the filter needs to be varied continuously, because the synchrotron tune will be varied from 0.01 to 0.02 to find the best operation point.

Table 1: The bandwidth of the filter and the estimated maximum loop gain.

Bandwidth	Maximum Gain 0° phase margin	Maximum Gain 45° phase margin
[kHz]	[dB]	[dB]
2.0	28.8	26.3
1.5	31.3	28.8
1.0	34.8	32.2
0.5	40.8	38.1

We made a new parallel comb-filter with seven channels. The bandwidth of the filter can be chosen from 0.5 kHz, 1.0 kHz and 2.0 kHz, and the center frequency can be varied from 0.8 kHz to 3.5 kHz continuously.

3 NEW PARALLEL COMB-FILTER

In the prototype parallel comb-filter, each center frequency of the band-pass filter is adjusted to $|n|\, f_{rev} - f_s$, where n is the mode number, f_{rev} is the revolution frequency and f_s is the synchrotron frequency. Since f_{rev} is about 100 kHz, if we made a seven channel comb-filter, the center frequency of the filter would range from 100 kHz to 700 kHz. Therefore, for some filters for higher modes, it is very difficult to reduce the bandwidth to less than 1 kHz. In the new parallel comb-filter, developed to circumvent this difficulty, the center frequency of each filter is converted to the baseband frequency. Figure 1 shows the block diagram of a channel in the new parallel comb-filter.

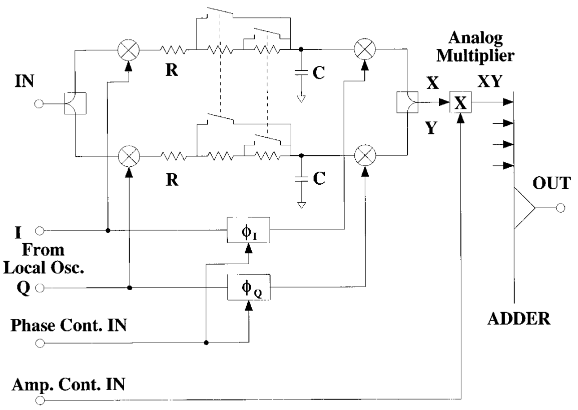

Figure 1: Block diagram of a channel in the new parallel comb-filter.

The input signal is divided in two and mixed with local oscillator signals, the frequency of which is adjusted to $|n| f_{rev} - f_s$, with a 90° phase difference between them. By controlling this frequency, the center frequency of the filter can track the variation of the synchrotron frequency. After mixing, the signal is filtered through a first-order RC low-pass filter. The bandwidth of the overall filter is twice the cut-off frequency of the low-pass filter and is changed in stepwise by switching the resistors in both circuits simultaneously. The filtered outputs are mixed with local oscillator signals again. By controlling the phase of the second mixing signals with respect to the first one, the overall filter can adjust the feedback phase.

4 RESULTS OF MEASUREMENT

We have performed an experiment of RF feedback with a new parallel comb-filter. Figure 2 shows the experimental setup which includes a parallel comb-filter and a low-power test cavity.

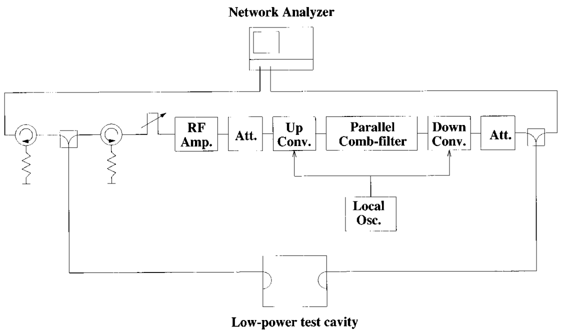

Figure 2: Block diagram of the experimental RF feedback loop which includes a parallel comb-filter and a cavity.

Figure 3 shows the measured open-loop response for the three cases of filter bandwidth, 0.5 kHz (solid line) kHz, 1.0 kHz (dotted line) and 2.0 kHz (broken line), as a function of normalized frequency $(f - f_{rf})/f_{rev}$. The maximum gain of the feedback loop is limited by the top-to-bottom amplitude ratio of the response, because the loop gain must be less than 0 dB at the bottom where the response becomes 180° out of phase. The figure clearly shows that the loop gain is increased by reducing the bandwidth of the filter. The maximum loop gain for the bandwidth of 0.5 kHz is 39 dB with a 0° phase margin and 36 dB with a 45° phase margin over a 1 MHz bandwidth. The measured loop gains are about 2 dB lower than the estimated ones given in Table 1.

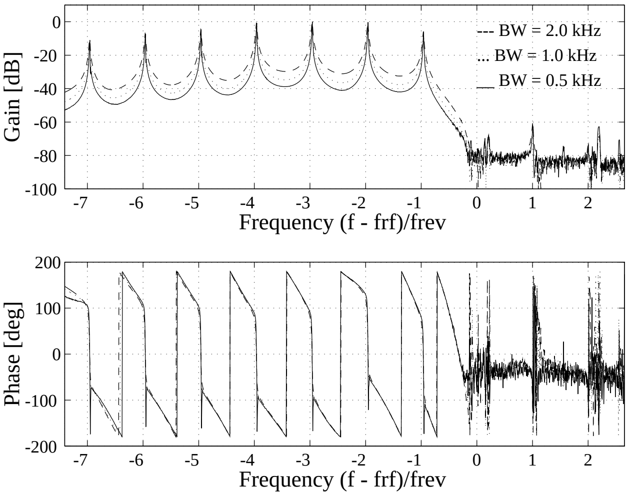

Figure 3: The measured open-loop response as a function of normalized frequency $(f - f_{rf})/f_{rev}$.

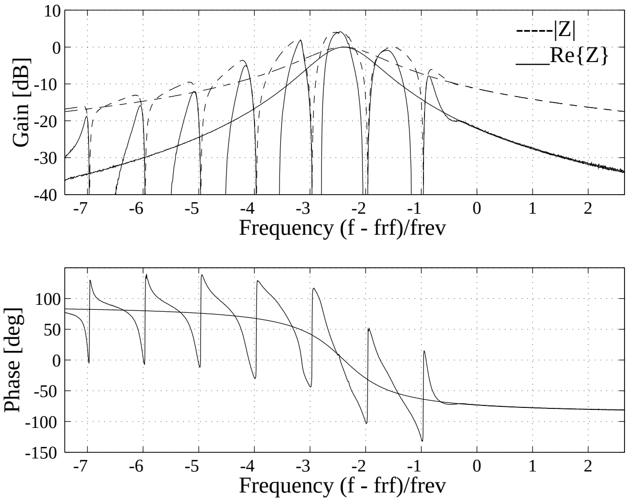

Figure 4: The measured closed loop response as a function of normalized frequency $(f - f_{rf})/f_{rev}$.

The measured closed loop response is shown in Figure 4. The top figure shows the normalized magnitude (broken lines) and the real part (solid lines) of the effective cavity impedance, with or without feedback. The bottom figure shows the phase response of the cavity, with or without feedback. The bandwidth of the filter and f_s (the difference between the center frequency of the filter and a revolution har-

Table 2: The real part of the impedance and growth time of coupled-bunch instabilities with or without parallel comb feedback

Mode	without feedback			with feedback		
	$\mathrm{Re}\{Z_+\}$	$\mathrm{Re}\{Z_-\}$	Growth time	$\mathrm{Re}\{Z_+\}$	$\mathrm{Re}\{Z_-\}$	Growth time
	[kΩ]	[kΩ]	[ms]	[kΩ]	[kΩ]	[ms]
+4	3.65	46.52	-0.70	3.65	72.60	-0.43
+3	5.10	156.10	-0.20	5.10	88.96	-0.36
+2	7.61	219.44	-0.14	7.61	-2.14	3.07
+1	12.51	62.73	-0.60	12.51	-44.79	0.52
0	48.04	49.32	-46.71	48.04	49.32	-46.71
-1	60.36	12.76	0.63	1.75	12.76	-2.72
-2	211.46	7.73	0.15	3.41	7.73	-6.93
-3	163.33	5.16	0.19	2.48	5.16	-11.13
-4	48.18	3.69	0.67	0.77	3.69	-10.23
-5	20.56	2.76	1.68	0.54	2.76	-13.43
-6	11.14	2.15	3.34	0.36	2.15	-16.73
-7	6.94	1.72	5.75	0.32	1.72	-21.43

monic) were adjusted to 0.5 kHz and 1.7 kHz respectively. The real part of the cavity impedance was reduced by 27 dB to 36 dB at the seven synchrotron upper sidebands.

The results of the measurements are summarized in Table 2, which gives the measured real part of the cavity impedance at the upper and lower sidebands of the -7 to $+4$ modes, and the corresponding growth time of the coupled-bunch instability, with or without feedback. All of the unstable modes from -1 to -7 were damped by the feedback. However, due to the small value of f_s, the feedback also reduced the real part of the impedance at the lower sidebands of $+1$ and $+2$, and made these two modes unstable. In order to circumvent this problem, we are planning to provide notches at these lower sideband frequencies.

5 CONCLUSIONS

The RF feedback using an improved parallel comb-filter was performed through a low-power test cavity. The real part of the cavity impedance was reduced by 27 dB to 36 dB at seven frequencies, 100 kHz apart from each other. In the next experiment where a klystron will be included, about the same loop gain will be obtained, because the parallel comb filter can compensate for a frequency-dependent group delay. In order to avoid the reduction of the lower sideband impedances of the $+1$ and $+2$ modes, the parallel comb-filter will be improved to provide notches at these frequencies.

6 REFERENCES

[1] “KEKB B-Factory Design Report”, KEK Report 95-7, 1995.

[2] S. Yoshimoto et al., “Experiment of the RF Feedback using a Parallel Comb Filter”, contributed to 1995 IEEE PAC and Int. Conf. High Energy Accelerators, Dallas, Texas, 1995.

[3] E. Ezura et al., “RF Feedback for KEKB”, contributed to Int. Workshop on Collective Effects and Impedance for B-Factories, Tsukuba, Japan, June 1995.