RF FEEDFORWARD SYSTEM FOR BEAM LOADING COMPENSATION IN THE J-PARC MR

Fumihiko Tamura*, Masanobu Yamamoto, Alexander Schnase, Masahito Yoshii, Chihiro Ohmori,
Masahiro Nomura, Makoto Toda, Taihei Shimada, Keigo Hara, Katsushi Hasegawa
J-PARC Center, KEK & JAEA, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195 Japan

Abstract

For acceleration of high intensity proton beams in the J-PARC MR, beam loading compensation is important. In the MA-loaded rf cavity in the MR, which has a Q-value in the order of 20, the wake voltage consists of the accelerating harmonic ($h = 9$) and the neighbor harmonics ($h = 8, 10$). We employ the rf feedforward method for the beam loading compensation, like in the J-PARC RCS, in which the impedance seen by the beam is greatly reduced by the feedforward. The full-digital feedforward system developed for the MR has a similar architecture to that of the RCS. The system compensates the beam loading of the important three harmonics ($h = 8, 9, 10$). We present the structure of the rf feedforward system. Also, we report the preliminary results of the beam tests.

INTRODUCTION

The synchrotrons of Japan Proton Accelerator Research Complex (J-PARC), the RCS and MR, employ magnetic-alloy (MA) cavities to realize high accelerating voltages. The parameters of the MR and its rf systems are listed in Table 1. At present, the MR delivers 1.0×10^{14} protons per pulse (ppp) to the neutrino experiment, which corresponds to 190 kW at the repetition period of 2.56 s, as routine operation [1].

The cavities of the MR are driven by single harmonic ($h = 9$) rf signals, while the cavities in the RCS are driven by dual-harmonic rf signals [2]. The Q-value is set to 22 to cover the accelerating frequency sweep from 1.67 MHz to 1.72 MHz. The cavity bandwidth covers also the neighbor two harmonics ($h = 8, 10$). Thus, the wake voltage in the cavity consists of the accelerating harmonic ($h = 9$) and the neighbor harmonics ($h = 8, 10$). The beam loading of the accelerating harmonic ($h = 9$) has effects on the motion of the bunch, and that of the neighbor harmonics ($h = 8, 10$) are the source of the periodic transient effects, which are possible causes of coupled bunch instabilities and rf bucket distortions.

Therefore, we developed a multi-harmonic rf feedforward system, for the three harmonics ($h = 8, 9, 10$).

WAKE VOLTAGE IN MR CAVITY

Typical harmonic components ($h = 8, 9, 10$) of the beam current and the wake voltage during the injection period are plotted in Fig. 1. The beam intensity is 7.8×10^{12} protons per bunch (6.25×10^{13} ppp). The data is taken by turning off the driving rf voltage in one of the cavities, so that the cavity voltage consists only of the wake voltage.

Table 1: Parameters of the J-PARC MR and its rf systems

circumference	1567.5 m
energy	3–30 GeV
beam intensity	(achieved) 1.0×10^{14} ppp
accelerating frequency	1.67–1.72 MHz
harmonic number	9
number of bunches	8
maximum rf voltage	280 kV
repetition period	2.56 s
No. of cavities	8
Acc. gaps in a cavity	3
cavity resonant frequency	1.72 MHz
Q-value of rf cavity	22

During the MR injection period, four RCS beam pulses, which consist of two bunches, are transferred into the MR to accumulate eight bunches. The injection interval is 40 ms and the four injection timings are called “K1”, “K2”, “K3”, and “K4”. The waveforms of the wall current monitor (WCM) and the cavity gap voltage monitor are captured for 10 ms after every “K-n” ($n = 1..4$) timing, and the harmonic analysis is performed. The Horizontal axis in Fig. 1 is the time accumulated in the oscilloscope.

After K1, the amplitudes of the harmonic components ($h = 8, 9, 10$) are fairly close, because only two bunches are circulating. With filling the buckets (at K2, K3, K4), the amplitude of the accelerating harmonic ($h = 9$) increases proportionally to the number of bunches. On the other hand, the increases of the neighbor harmonics ($h = 8, 10$) are smaller than that of the accelerating harmonic at K2, and finally they become fairly smaller than ($h = 9$) at K4. The oscillations of the amplitude of the components ($h = 8, 10$) are observed. This is because the phases of the dipole oscillations of the bunches injected from K1 to K4 are different.

Additionally, the neighbor harmonic components ($h = 8, 10$) of the wake voltage are smaller than that of ($h = 9$), because the frequencies of them (1.48 and 1.85 MHz) are farther from the resonant frequency than the frequency of ($h = 9$), 1.671 MHz. One can see that the periodic transient beam loading due to the neighbor harmonics is severest when two or four rf buckets are filled (K1, K2).

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[*] fumihiko.tamura@j-parc.jp

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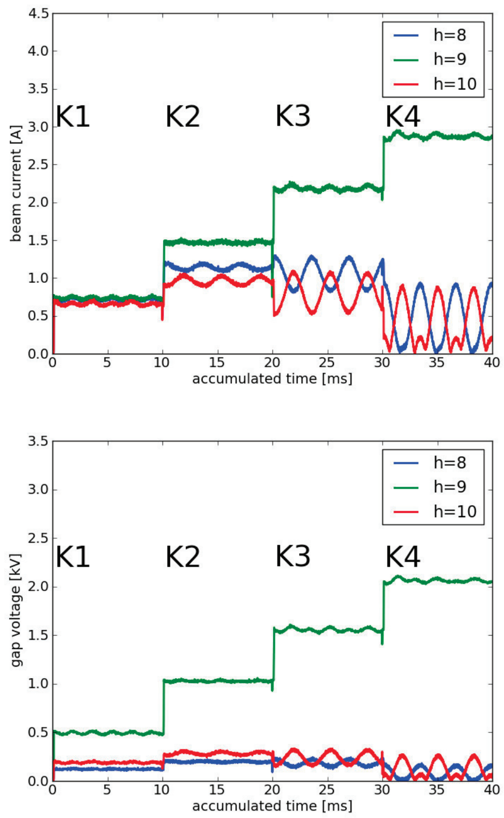

Figure 1: Harmonic components of the beam current (top) and the wake voltage (bottom) during injection period.

When eight buckets are filled, the wake voltages of ($h = 8, 10$) are small because the harmonics components of the beam current are small.

The rf gap voltage during injection period is 4–6 kV. The accelerating harmonic component ($h = 9$) of the wake voltage is comparably high at K4 with this beam intensity.

Therefore, the beam loading compensation is a key to achieve the higher beam intensity and power.

MULTI-HARMONIC FEEDFORWARD SYSTEM

We developed the full-digital feedforward system with a similar architecture to that of the RCS [3]. The system compensates the beam loading of the three harmonics ($h = 8, 9, 10$).

The block diagram of the feedforward system is illustrated in Fig. 2. The system uses the WCM signal to generate the feedforward compensation signal, so that the wake voltage can be canceled. The I/Q detection technique is used to pick up the I/Q vectors of the WCM signal for the selected harmonics ($h = 8, 9, 10$). The I/Q vectors of the harmonics are distributed to the modules for 8 cavities. The I/Q detection blocks use phase reference signals generated by the direct digital synthesis (DDS) technology. The frequency sweep is perfectly synchronized to the driving rf frequency sweep.

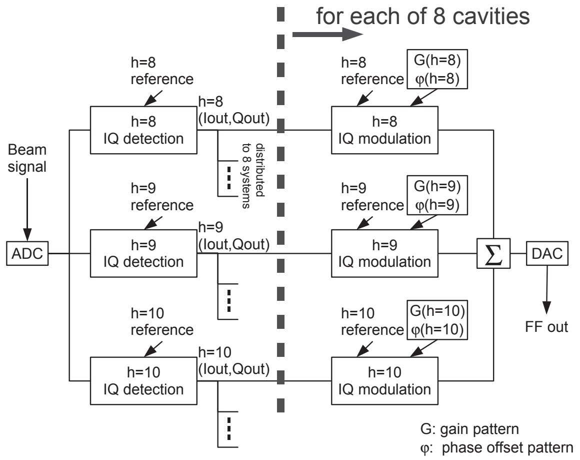

Figure 2: Block diagram of the multi-harmonic feedforward system.

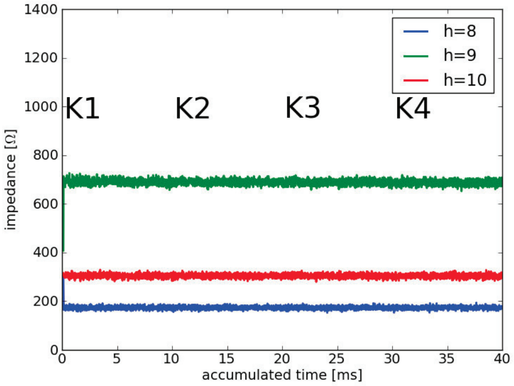

Figure 3: Impedances seen by the beam during the injection period without feedforward. The horizontal axis is the accumulated time.

By using I/Q modulation, feedforward compensation rf signals are generated with gain and phase patterns for the three harmonics. The phase references of the harmonics are also used. The compensation signals for the harmonics are summed up and the signal is converted by a D/A converter. Finally, the compensation signal is sent to the summation amplifier, so that the cavity is driven by a superposition of the driving rf and the feedforward signal.

Essentially, the feedforward system works as a tracking bandpass filter, whose passbands at the harmonics ($h = 8, 9, 10$) follow the frequency sweep with programmed gain and phase patterns.

PRELIMINARY BEAM TEST

A preliminary beam test has been performed by using a cavity without driving the accelerating rf voltage, while this situation is not a standard operation. The other seven cavities were driven by a normal rf voltage pattern. The WCM signal and the cavity gap voltage signal were taken

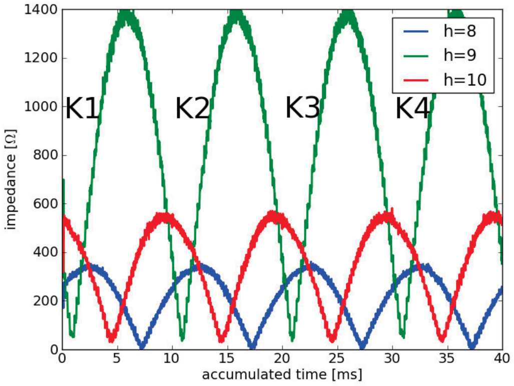

Figure 4: Impedances seen by the beam with feedforward using a constant gain and the periodical phase sweeps.

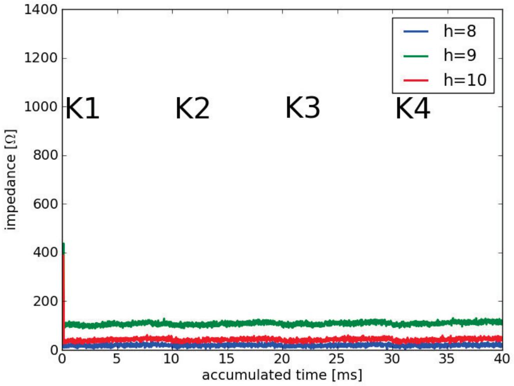

Figure 5: Impedances seen by the beam with feedforward using constant gain and phase patterns.

by an oscilloscope, and the harmonic analysis of the waveforms was performed. In this test, the bunches are injected only at the K1, thus, two bunches were circulating in the MR ring.

The cavity gap impedance is obtained by the following equation (frequency domain),

$$V_{\rm cav}(h,t) = Z_{\rm cav}(h,t) \cdot I_{\rm beam}(h,t), \tag{1}$$

where h is the selected harmonic, t the time, $Z_{\rm cav}$ the gap impedance. $V_{\rm cav}$ and $I_{\rm beam}$ are the harmonic component of the gap voltage and the beam current, respectively. By the measured harmonics components, $V_{\rm cav}(h,t)$ and $I_{\rm beam}(h,t)$, one can calculate the impedance seen by the beam, $Z_{\rm cav}(h,t)$.

The amplitudes of the impedances seen by the beam during the injection period without feedforward are plotted in Fig. 3. As described in the previous section, the horizontal axis is the accumulated time. Since the revolution frequency is constant (186 kHz) during the injection period, the impedance seen by the beam, which is the cavity impedance itself, is constant. The impedance of the accelerating harmonic ($h = 9$) is 685 Ω, and impedances of the neighbor harmonics ($h = 8, 10$) are 167 Ω and 300 Ω, respectively.

Next, we applied the feedforward signal. The cavity voltage was a superposition of the wake voltage and the feedforward signal. To find the optimum phase for the injection period, we swept the phase of the feedforward signal. We used a periodical linear sweep pattern from 0 to 360 degrees. The sweep period was set to 10 ms. The phase offsets for the harmonics ($h = 8, 9, 10$) were 90, 0, -90 degrees, respectively. The constant gain pattern, 20000 (digital value), is used for all harmonics.

The impedances seen by the beam with feedforward using the phase sweeps are plotted in Fig. 4. One can see periodical variations of the impedances seen by beam. Since the phase sweep covers 0 to 360 degrees, both of reductions and increases of the impedance are observed. The minimum points are found at 7.2 ms, 1 ms, and 4.5 ms for $h = 8, 9, 10$, respectively. At the points, the feedforward phases of the harmonics ($h = 8, 9, 10$) are 100.8 , 35.9, and 158.4 degrees, respectively.

Then, we set the constant patterns. The gain was same, 20000, and the constant phases of the harmonics were 100.8 degrees ($h = 8$), 35.9 degrees ($h = 9$) and 158.4 degrees ($h = 10$). The impedances seen by the been with feedforward using the constant patterns are plotted in Fig. 5. Comparing to Fig. 3 without feedforward, one can notice remarkable impedance reductions for three harmonics. The impedances of the harmonics ($h = 8, 9, 10$) were reduced to 18, 103, and 42 Ω, respectively.

SUMMARY AND OUTLOOK

We developed the multi-harmonic feedforward modules for beam loading compensation in the J-PARC MR. The preliminary beam test of the feedforward system has been performed and the impedances seen by the beam during the injection period were successfully reduced by using constant gain and phase patterns.

We are going to apply the commissioning methodology of the feedforward [3], which is used in the RCS to improove the feedforward patterns. By the methodology, impedance reductions with driving rf voltages from the injection to extraction are foreseen.

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