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Baseband simulation model of the vector rf voltage control system for the J-PARC RCS

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Abstract. Vector rf voltage feedback control for the wideband magnetic alloy cavity of the J-PARC RCS is considered to be employed to compensate the heavy beam loading caused by high intensity proton beams. A prototype system of multiharmonic rf vector voltage control has been developed and is under testing. To characterize the system performance, full rf simulations could be performed by software like Simulink, while the software is proprietary and expensive. Also, it requires much computing power and time. We performed the simplified baseband simulations of the system in z-domain by using free software, the Python control library. It seems to be beneficial for searching the parameters that the baseband simulation can be performed quickly. In this presentation, we present the setup and results of the simulations. The simulations well reproduce the open and closed loop responses of the prototype system.

1. Introduction

After a decade of operation, we are considering to replace the low level rf (LLRF) control system for the rapid cycling synchrotron (RCS) in the Japan Proton Accelerator Research Complex (J-PARC) with a new system. The parameters of the RCS and its rf system are listed in table. 1. An important feature of the LLRF control system for the RCS is the multiharmonic beam loading compensation due to high intensity proton beams in the wide band magnetic alloy (MA) cavity with a low Q value of 2. The wake voltage in the cavity consists of several harmonics. A multiharmonic rf feedforward system, which generates compensation signals using beam signals, is implemented in the existing system. The multiharmonic feedforward system works well [1], however, we found some practical disadvantages of the feedforward method due to its open loop configuration during high intensity beam tests. Hence we consider to employ a vector voltage feedback control in the new LLRF system.
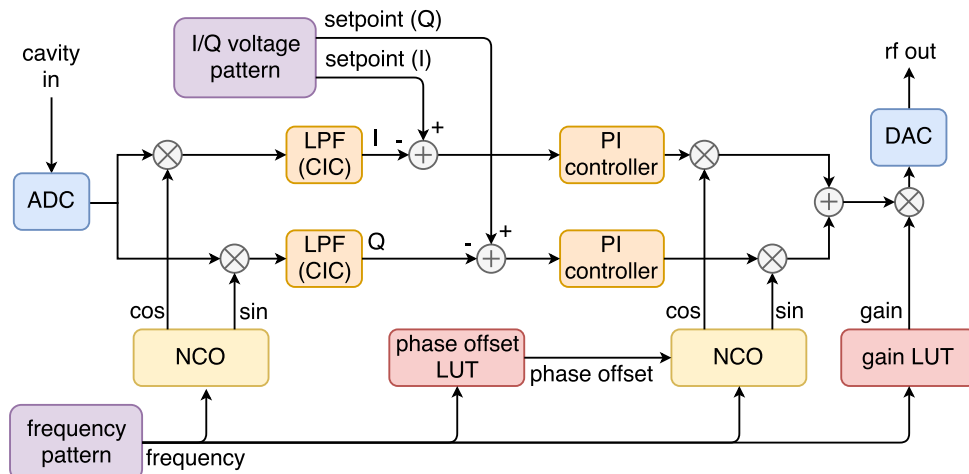
A multiharmonic vector voltage control prototype system has been developed and is under testing. Matlab Simulink[2] is widely used to simulate the behavior of such systems including rf cavities and amplifier chains. It is a powerful tool, while it is proprietary and expensive and requires much computing power and time to calculate frequency responses. There are several free softwares, such as the Python control library[3] and Scilab[4], for numerical computation of feedback systems based on the Laplace transform or Z-transform. We have performed simplified baseband simulations using the Python control library. The baseband analysis can be performed

Table 1. Parameters of the J-PARC RCS and its rf system.

parameter	
circumference	348.333 m
energy	0.400–3 GeV
beam intensity	(achieved) 8.3×10^{13} ppp
accelerating frequency	1.227–1.671 MHz
harmonic number	2
maximum rf voltage	440 kV
repetition rate	25 Hz
No. of cavities	12
Q-value of rf cavity	2

quickly on a PC. In this article, we present the setup and results of the simulation of the feedback system with code examples for the Python control library.

Figure 1. Simplified block diagram of the vector voltage feedback for one harmonic.

2. Multiharmonic vector voltage control prototype system

The multiharmonic vector voltage control prototype system handles six harmonics to cover the wide frequency response of the MA cavity. A simplified block diagram for one harmonic is shown in figure 1. The system runs at the clock frequency of 144 MHz. The cavity voltage monitor signal is directly digitized by an ADC. The complex amplitude (I/Q) of the voltage signal is obtained by I/Q demodulation. In the I/Q demodulator, 5-stage CIC (cascaded integrator and comb) filters are employed to realize the narrow bandwidth required to separate the neighbor harmonics. The minimum revolution frequency is minimum at the injection, about 0.6 MHz. The delay in the comb is set to be 512 system clocks. The complex amplitude is compared to the I/Q voltage pattern. Through the PI controller and the I/Q modulator, the driving rf signal is generated. The first order integrator is implemented in the PI controller.

The digital frequency signal is picked up from the frequency pattern memory every 1 μs. The frequency signal is used for the numerically controlled oscillators (NCOs) and for addressing of

the phase offset and gain lookup tables (LUTs). The accelerating frequency of the RCS varies from 1.2 MHz at the injection to 1.7 MHz at the extraction. The phase shift of the 1-turn transfer function for the wide frequency range due to the cable delay and the phase response of the cavity is compensated by the phase offset LUT, which gives a phase offset between the I/Q demodulator and modulator so that the phase of the 1-turn transfer function is constant. Also, the gain LUT compensates the amplitude response of the cavity. By adjusting the phase offset LUT, the feedback loops for the I and Q can be separated. In other words, one can model and analyze the feedback system as a simple SISO (single-input single-output) system.

3. Baseband models
3.1. Transfer function of the prototype
By setting the integrator gain to zero, the system response simply consists of the CIC filter response and the time delay in the system. In the z-domain, the transfer function of a CIC filter is

$$H_{\mathrm{CIC}}(z) = \left(\frac{1 - z^M}{1 - z^{-1}} \right)^N,\tag{1}$$

where M is the differential delay and N the number of stages. The way to define the transfer function using the Python control library is similar to Matlab or Scilab. A definition of the function to implement a CIC filter is as follows.

```
import numpy as np
from control.matlab import *
from functools import reduce

def gen_cic_ss(mm=32,nn=1,dt=True):
    num=np.zeros(mm+1);num[0]=1;num[-1]=-1
    den=np.zeros(mm+1);den[0]=1;den[1]=-1
    tf1=tf(num,den,dt)/mm
    ss1=tf2ss(tf1)
    syscics=reduce(lambda x,y:x*y,nn*[ss1,])
    return(syscics)
```

The Matlab compatibility package (`control.matlab`) provides the common functions corresponding to commands available in Matlab, while the package is not dependent on Matlab. In contrast to the Laplace transform, pure delay can be expressed as $H_{\mathrm{delay}}(z) = z^{-\mathrm{dclk}}$ without approximation, where dclk is the integer part of (time delay) × (clock frequency). Finally, the total transfer function $H_{\mathrm{CIC}} \cdot H_{\mathrm{delay}}$ is evaluated to obtain the frequency response.

A comparison between measured and simulated frequency responses is shown in figure 2. The horizontal axis is the frequency difference from the center frequency. The time delay is set 2.2 μs so that the phase response of the simulation reproduces the phase measurement. The simulation result agree with the measurement. As described in the previous section, the minimum harmonic separation is 0.6 MHz. For the frequency above 0.6 MHz, the attenuation is better than 85 dB; the separation of the harmonics is achieved by this filter configuration.

The long delay of 2.2 μs consists of the inevitable latency of the serial connection between the ADC and FPGA (about 700 ns) and other digital delay. We will optimize the FPGA codes to minimize the digital delay. The 5-stage CIC filter itself has much phase shift in the passband. The feedback bandwidth is limited by both of the time delay and the phase shift of the CIC filter.
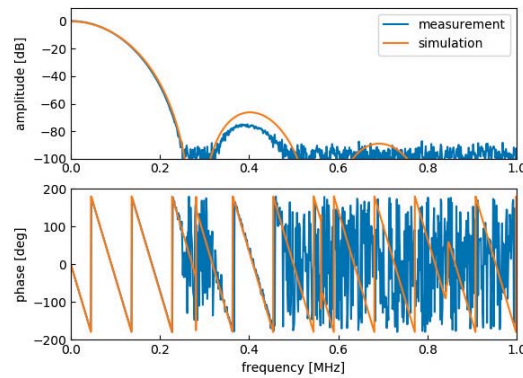
Figure 2. Comparison between the measured and simulated frequency responses.

3.2. Feedback simulation

The measurement setup of the closed loop gain with feedback is illustrated in figure 3. Two directional couplers are inserted between the system and DUT (device under test), which consists of the amplifier chain and the cavity. The transfer function S_{21} from point A to B is measured by a network analyzer. The injected signal from the network analyzer is the disturbance for the feedback loop. The setpoint is set to zero in this measurement. The measured closed loop gains with various proportional (P) and integrator (I) gain are plotted in figure 4. In the plot, P and I are digital values for setting. The response is normalized by using the response without feedback. One can see that suppression better than 30 dB is obtained with the integrator gain and the feedback bandwidth depends on the integrator gain.
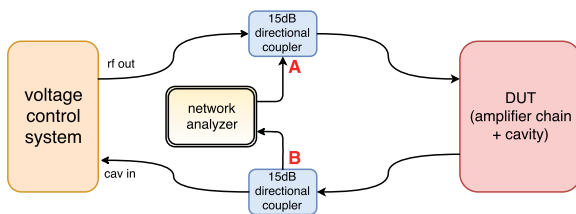

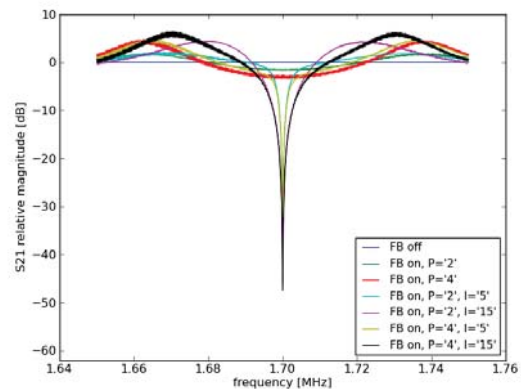**Figure 3.** Setup of the closed loop gain measurement.

Figure 4. Measured closed loop responses with various PI gains. The amplitude is normalized by the response without feedback.

The baseband model for the feedback simulation is shown in figure 5. As described in the previous section, the feedback loop can be treated as a SISO system with the proper setting of the phase offset LUT and the DUT becomes a simple gain. The transfer function of the PI
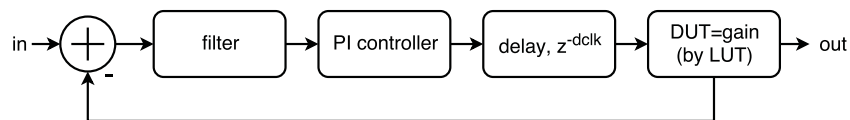
Figure 5. The feedback model in the baseband.

controller following the CIC filter is

$$H_{\mathrm{PI}}(z) = K_P + K_I \frac{1}{1 - z^{-1}}, \tag{2}$$

where K_P and K_I are the proportional and integrator gains, respectively. The 1-turn (open loop) transfer function is

$$H_{\mathrm{CIC}} \cdot H_{\mathrm{PI}} \cdot H_{\mathrm{delay}} \cdot G, \tag{3}$$

where G is the DUT gain. The closed loop transfer function is obtained by the `feedback()` function of the Python control library:

```
sysfb=feedback(1,sys1turn)
```

By adjusting the time delay and the gain G, the model can reproduce the system responses. The simulated open and closed loop gain and the measured closed loop gain are plotted in figure 6, with $P = 4$ and $I = 15$ (digital values). The time delay and G are set to 3.9 μs and 0.95, respectively. The time delay consists of the latency of the prototype system and the cable delay. The cable length between the rf control room and the tunnel is more than 300 m round trip. For both of the amplitude and phase responses of the closed loop gain, the simulation and measurement agree nicely. For other proportional and integrator gain setting, the simulation using the same time delay and gain G shows good agreement with the measurement.
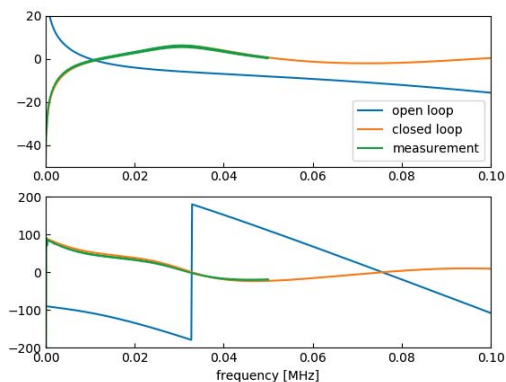

Figure 6. The simulated open and closed loop gain and the measured closed loop gain with $P = 4$ and $I = 15$ (digital values). The time delay and G are set to 3.9 μs and 0.95, respectively.
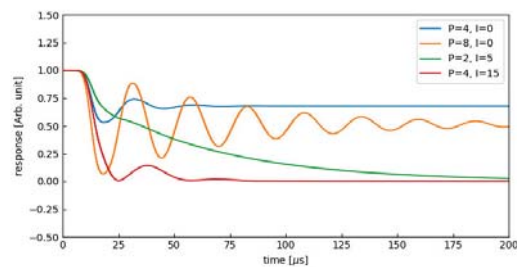

Figure 7. Simulated step responses with various PI gains.

The step response of the feedback system also can be simulated. In figure 7, the simulated step responses with various PI gains are plotted. One can see that high feedback gain can not

be realized in case of the proportional gain only. The system is close to the unstable condition with $P = 4$ and $I = 0$. $P = 2$ and $I = 5$ (digital values) were used for the initial beam test. The setting is not optimum, because of the slow step response. Higher PI gain setting, $P = 4$ and $I = 15$, is preferred to achieve faster response.

4. Summary and outlook

A multiharmonic vector voltage control prototype system has been developed and under testing. We developed baseband models to characterize the system behavior. The baseband simulations well reproduce the transfer function of the prototype system and the closed loop responses of the voltage feedback. The baseband simulation can be performed very quickly, less than one minute, hence it is useful for searching the parameters.

It seems that the current configuration with the 5-stage CIC filter has much phase shift in the passband. We will examine the other configurations using the baseband simulation. CIC filters with reduced number of stages and leaky integrators are possible candidates.

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