

# CORRECTION OF PHASE AND AMPLITUDE ERROR OF RF MODULATOR AND DEMODULATOR

T. Ohshima<sup>#</sup>, H. Maesaka, N. Hosoda, S. Matsubara, Y. Otake, RIKEN/SPring-8, Hyogo, Japan  
M. Yamaga, JASRI/SPring-8, Hyogo, Japan

### Abstract

The construction of XFEL/SPring-8 project is in progress. In this accelerator very high stabilities are required to the rf amplitude and the phase of the accelerating cavities. At the most severe case, the stabilities of 0.01% (rms) in the amplitude and 0.1 degree (rms) in the phase of a C-band cavity voltage are required. To make such a stable rf field, we developed a high-speed DAC and an ADC, and an IQ (In-phase and Quadrature) modulator and a demodulator to control and detect the low level rf signals. High setting and detecting accuracy of the modules are preconditions to achieve good stability. But the developed modules had some errors such as offsets and gain errors due to the requirement of the high-speed operation. These errors degrade the performance of the feedback control processes used to stabilise the rf amplitude and the phase. So we developed a calibration procedure of the IQ demodulator. By using this procedure we could reduce the amplitude and the phase errors of the IQ modulator at 5712 MHz from 10 % p-p to 0.7 % p-p and from 6 degree p-p to 0.3 degree p-p, respectively. Once we obtain a calibrated demodulator, we can calibrate the IQ modulator up to the same accuracy of the demodulator by using similar procedure.

### INTRODUCTION

The XFEL/SPring-8 is under construction to provide an intense and coherent X-ray in a wavelength of 0.1 nm by using an electron beam with an energy of 8GeV, a bunch length of several tens fs, and a peak current of 3 kA. The accelerating cavities of C-band and its sub-harmonic cavities are used at the XFEL machine. To obtain such a short bunch beam with high peak current, it is necessary to control the amplitude and the phase of the rf field in the accelerating cavity very accurately. At the most severe case, the stabilities of 0.01% (rms) in the amplitude and 0.1 degree (rms) in the phase of a C-band cavity are required. To control the amplitude and phase of the rf field, we developed an IQ modulator and an IQ demodulator [1,2], and a high speed DAC and an ADC [3]. Feedback control loops using these modules are employed to keep the phase and amplitude of the rf field in the cavity constant. It is desired that the systematic error of these modules, such as a phase setting deviation, should be as small as possible. It is because the systematic errors raise many problems: degradation of the feedback control performance, misunderstanding of the XFEL machine behaviour during a beam tuning, and so on. To reduce the systematic errors of the modules, we should

measure the errors in a first step, and then we should correct the reading values using the known errors. We set the target values of the systematic errors less than ten times of the required stabilities. The reason we relaxed the values is that in general the accuracy does not have to be as high as the precision because relative values are sometimes enough to control the feedback system, for example. In this paper, we describe the details of how to measure the systematic errors of an IQ demodulator, how to correct them, the performance of the correction, and its extension.

### MEASUREMENT OF SYSTEMATIC ERROR OF RF DEMODULATOR

#### Configuration of the RF Demodulator

An rf demodulator is used to measure the amplitude  $r_1$  and the phase  $\phi$  of the rf input signal relative to the reference signal whose amplitude is  $r_0$  and the frequency is  $f_0$ . Fig. 1 shows a schematic view of the IQ demodulator. The reference signal is split into two signals (I and Q). The phase difference between these two signals is adjusted to be 90 degree. The rf input signal is also split into two signals. In this case the phase difference of them is set to be 0 degree. These signals are fed to two mixers and converted to baseband signals ( $V_i$  and  $V_q$ ). The amplitude of the baseband signal  $r$  can be expressed as  $r = \sqrt{V_i^2 + V_q^2}$  and is proportional to the amplitude of the rf input signal with a constant factor  $r_0 * c_r$ . The phase of the base band signal  $p$  can be expressed as  $p = \tan^{-1}(V_q / V_i) = \phi + c_p$ , where  $\phi$  is the phase of the rf input signal and  $c_p$  is a constant value. The ADC used to detect the baseband signals has a 12-bit resolution, +/- 1 V full scale, four input channels and a sampling rate of 238 Ms/s. Its size is one VME unit width. It has a 4 Mbytes memory and can store waveforms up to 1k samples with 2k word data points. The data stored in the ADC is transferred to a

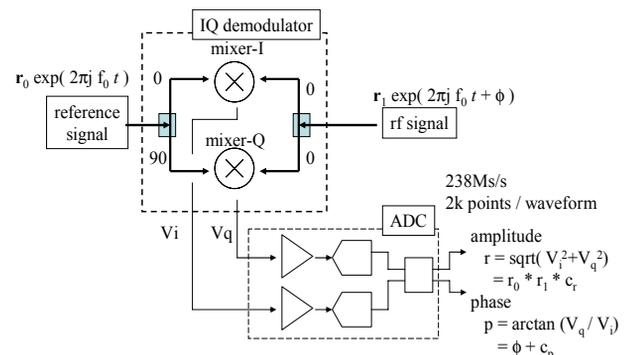


Figure 1: Schematic view of the IQ demodulator.

<sup>#</sup> ohshima@spring8.or.jp

GUI program or a database through a control system implemented in MADOCA (Message And Database Oriented Control Architecture) framework [4].

### Sources of the Systematic Error

The error of the amplitude  $\Delta r$  and the phase  $\Delta p$  can be expressed as follows,

$$\Delta r = r / (r_1 * r_0 * c_r) - 1,$$

$$\Delta p = p - \phi - c_p,$$

where  $r$  and  $p$  is the measured amplitude and the phase of the baseband signals,  $r_1$  and  $\phi$  are those of the rf input signal, and  $r_0$ ,  $c_r$ , and  $c_p$  are constants. If the demodulator is ideal one, the detected amplitude  $r$  is constant, i. e.  $\Delta r$  is zero, for any value of  $\phi$ . The phase difference  $\Delta p$  between the detected phase  $p$  and that of the input signal  $\phi$  is also zero at a condition of  $c_p$  is zero. But if there were some errors, the values of  $\Delta r$  and  $\Delta p$  were finite values and had variation as the input phase  $\phi$ .

The possible sources of the errors  $\Delta r$  and  $\Delta p$  based on the above mentioned configuration are as follows;

- Offset: The baseband amplifiers used in the IQ demodulator and the ADC have an offset voltage. The rf leakage from the reference signal port to the rf input port of the mixer also cause an offset in  $V_i$  or  $V_q$ .
- Gain error: The sensitivity differences of the mixers and the gain difference between the baseband amplifiers on the  $V_i$  and  $V_q$  signal transmissions cause gain errors.
- Phase error of an rf signal splitter: The phase error at the two power splitter in the IQ demodulator cause mixing of the I signal and the Q signal.
- Saturation of the rf amplifier, the baseband amplifier and/or the mixer: The saturation of these modules causes non-linearity of the amplitude and the phase detection.

Next, we show a numerical example based on the above mentioned argument. The amplitude and the phase errors caused by a finite offset voltage at the  $V_i$  output of the IQ demodulator are shown in Fig. 2. In this case we set the amplitude of the rf input signal  $r_1$  is 100mV and the offset voltage at the  $V_i$  output is 10 mV. We can see obvious variation as the input phase of  $\phi$  in  $\Delta r$  and  $\Delta p$ , and their

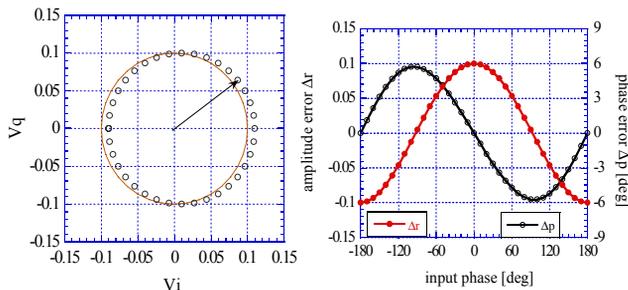


Figure 2: The calculated amplitude and phase error with an offset voltage in the  $V_i$  signal.

maximum variations are 20 % in p-p and 12 degree in p-p, respectively.

### Measurement of the Systematic Error

What we want to know is the values of the errors  $\Delta r$  and  $\Delta p$  of the modulator at a given amplitude  $r_1$  and phase  $\phi$  of the rf input signal. So we measure the response of the values of  $\Delta r$  and  $\Delta p$  as a function of the input phase  $\phi$  at a fixed amplitude  $r_1$  as a first step. We fed a frequency-shifted signal from a signal generator to the demodulator as shown in Fig. 3. The frequency of the signal generator is set to  $f_0 + \Delta f$ . The phase of the input signal  $\phi$  relative to the reference signal is changed proportional to the elapsed time  $t$  expressed as  $\phi(t) = 2\pi\Delta f^*t$ . By recording the voltages of the baseband signal of the demodulator  $V_i$  and  $V_q$ , with a constant time interval  $\Delta t$ , we can obtain the amplitude  $r$  and the phase  $p$  as a function of the input phase  $\phi$  with a constant phase interval  $\Delta\phi = 2\pi\Delta f^*\Delta t$ .

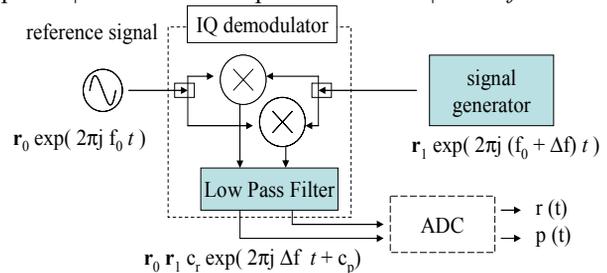


Figure 3: A setup to measure the amplitude and the phase errors of the IQ demodulator. The frequency-shifted signal is fed to the IQ demodulator, which is equivalent to scan the input rf phase.

We applied the above method to our C-band IQ demodulator. The frequency of the signal generator was set to 5712MHz + 0.2MHz. The output voltage of the demodulator was recorded by using the ADC with a time interval  $\Delta t$  of 4.2 ns up to 2k points. Figure 4 shows the measured  $r(i)$  and  $p(i)$ , where  $i$  is the number of the data point. The relation between the data number  $i$  and the phase  $\phi$  is expressed as

$$\phi(t) = 2\pi\Delta f^*t = 2\pi\Delta f^*\Delta t*i = 0.3 \text{ degree} * i.$$

In this case, the total phase shift is  $2\pi*1.9$  for a time duration of 8.4  $\mu s$ . In the Fig. 4, we can see a modulation

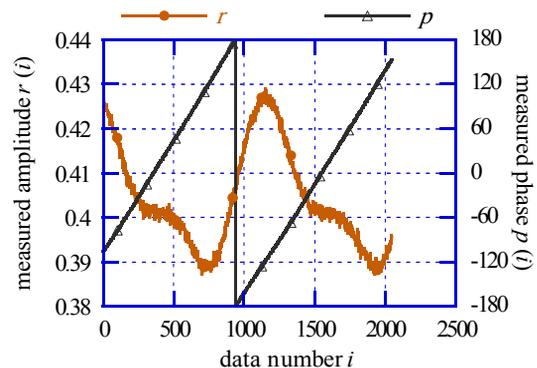


Figure 4: The readout of the IQ demodulator. The frequency shift is 200 kHz. The sampling rate is 238 Ms/s.

of the detected amplitude  $r(t)$ . From these data, the systematic errors of the amplitude  $\Delta r$  and the phase  $\Delta p$  are calculated. Figure 5 shows the extracted errors  $\Delta r$  and  $\Delta p$  as a function of a measured phase  $p$ . The data point represents an averaged value using 10 data points with a phase step of 10 degree. In this case, the maximum values of  $\Delta r$  and  $\Delta p$  are about 10% and 6 degrees in p-p, respectively.

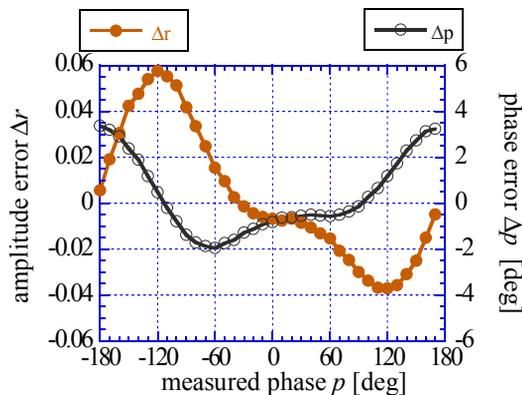


Figure 5: The extracted amplitude and the phase errors using the data shown in the Fig. 4.

### CORRECTION OF THE SYSTEMATIC ERROR

Once the error values  $\Delta r(\phi)$  and  $\Delta p(\phi)$  as a function of the input phase  $\phi$  can be obtained, the corrected amplitude  $r_c(\phi)$  and the phase  $p_c(\phi)$  can be calculated as follows,

$$r_c(\phi) = r(\phi) * (1 + \Delta r(\phi)),$$

$$p_c(\phi) = p(\phi) + \Delta p(\phi).$$

To reduce the amount of the calculation in the correction, it is desired to express the values of  $\Delta r(\phi)$  and  $\Delta p(\phi)$  by an appropriate function with a small number of parameters. As can be seen in the Fig. 5, the values of  $\Delta r(\phi)$  and  $\Delta p(\phi)$  have a periodic structure in the parameter  $\phi$ . So we use the Discrete Fourier Transform (DFT) for the approximation of this periodic structure. The DFT calculation shows that the values of the first and second order coefficients are significant. The value of the first order corresponds to the offset of the demodulator. The second order coefficient corresponds to the gain error and/or a tilt of the IQ axis from a right angle. By using these obtained coefficients up to second order, the correction was applied to the measured amplitude and the phase. Figure 6 shows the result. The remained amplitude and the phase errors are 0.7% p-p and 0.3 degree p-p, respectively, which are about one-tenth of the values without correction.

The errors of  $\Delta r$  and  $\Delta p$  of the IQ demodulator at the different input amplitude  $r_1$  were measured by changing the power level of the signal generator shown in Fig. 3. From the measured data, we could obtain a 2-dimensional data table of the Fourier coefficients for approximation of the values of  $\Delta r(r, \phi)$  and  $\Delta p(r, \phi)$ . By using this table, we can make a correction to any values of the amplitude

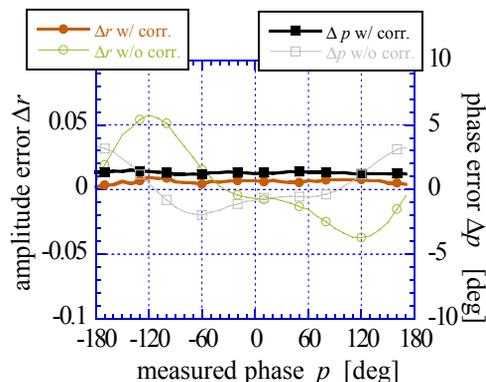


Figure 6: The errors of the amplitude and the phase of the IQ demodulator with and without correction.

and the phase of the IQ demodulator. This coefficient table is stored in a file and the correction is done by a program running on the CPU of the VME chassis.

By using the calibrated reference IQ demodulator, the amplitude and phase error of the IQ modulator can be measured and corrected by a similar procedure with the same accuracy of the modulator.

### SUMMARY

We developed a calibration procedure for an IQ demodulator. The systematic error of the IQ demodulator was measured by feeding a frequency-shifted signal, which is equivalent to scan the input rf phase. From the values of the amplitude and the phase sampled by an ADC with a fixed time interval, the systematic errors of the amplitude and the phase were calculated. The errors were expressed with a small number of DFT coefficients. By using these coefficients the systematic error was reduced from 10% p-p to 0.7% p-p and from 6 degree p-p to 0.3 degree p-p in the amplitude and in the phase, respectively. The phase error could be reduced smaller than the target value we set. The amplitude error was somewhat larger than the target value. By using the calibrated reference IQ demodulator, an IQ modulator can be calibrated with a similar procedure. Further reduction of the errors, the performance test combining the calibrated modules, such as the modulator/demodulator and the DAC/ADC, are our next step.

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