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ADAPTIVE FEEDFORWARD CONTROL DESIGN BASED ON SIMULINK FOR J-PARC LINAC LLRF SYSTEM

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Abstract

In j-parc linac, for dealing with high beam loading effect, an adaptive feedforward control method which based on iterative learning control was put forward. At the same time, in order to verify its effectiveness before it is officially put into use, an llrf system simulation model was built in simulink, matlab. In this paper, the architecture of llrf system simulation model will be introduced. The result of iterative learning control (ILC) is summarized.

INTRODUCTION

For current llrf system in j-parc linac, the means to reduce the beam loading effect are feedback control and feedforward compensation [1, 2]. In 324MHz low-β section, which consist of RFQ (Radio Frequency Quadrupole), DTL (Drift Tube Linac) and SDTL (Separated-type DTL), only by these two methods it can achieve very good control effect. However, in 972MHz high-β section, which is made up of 400MeV ACS (annular coupled structure) linac and 600MeV superconducting cavity linac, the stability of the waveform is still need to be improved. Figure 1 shows the RF–pulse amplitude waveforms of RFQ and ACS station one, respectively. The amplitude stability of RFQ cavity is about ±0.25%, but in ACS1, this value is larger than ±0.75%. To solve this problem, we need a new control method.

Iterative learning control（ILC）is a technique for improving the transient response and tracking performance of processes, machines, equipment, or systems that execute the same trajectory, motion, or operation over and over [3]. And in most cases, llrf system, when it works in pulse mode, perform the same operation repeatedly with high precision and under the same operating conditions, which satisfy the ILC notion that the performance of a system that executes the same task multiple times can be improved by learning from the previous executions.

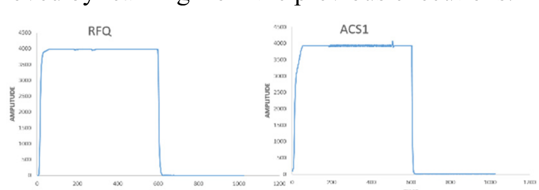

Figure 1: RF-pulse waveform in RFQ&ACS1 cavities.

Figure 2 shows the basic idea of iterative learning control, where u_k is system input, y_k is system output, y_d is reference signal and u_{k+1} is the next system input after the iterative operation. All the signals shown are assumed to be defined on a finite intervalt $\in [0,\ t_f]$. The subscript k indicates the trial or repetition number. The continuous-time version of the learning control algorithm that we used in this experiments is

$$u_{k+1}(t) = u_k(t) + \Gamma e_k(t+1). \tag{1}$$

In this equation, Γ is control gain ($0 < \Gamma < 1$), error$e_k(t) = y_k(\mathrm{t}) - y_d(\mathrm{t})$.

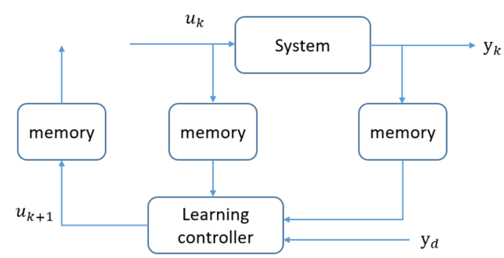

Figure 2: Standard iterative learning control scheme.

DESIGN OF LLRF SYSTEM IN SIMULINK

A classical LLRF system consists of the following parts: feed forward base input, cavity, output, reference model, PI controller and beam loading model. Both of them can be treated as black box. When the design of all the components is completed and then we can make them a system.

For cavity model, according to cavity theory, we can get cavity state space equation as below:

$$\frac{d}{dt}\begin{bmatrix} v_{cr} \\ v_{ci} \end{bmatrix} = \begin{bmatrix} -w_{1/2} & -\Delta w \\ \Delta w & -w_{1/2} \end{bmatrix}\begin{bmatrix} v_{cr} \\ v_{ci} \end{bmatrix} + w_{1/2} R_L \begin{bmatrix} I_u \\ I_i \end{bmatrix}. \tag{2}$$

Then according this state space equation we can build the structure of cavity simulation model [4] which shown in the Fig. 3.

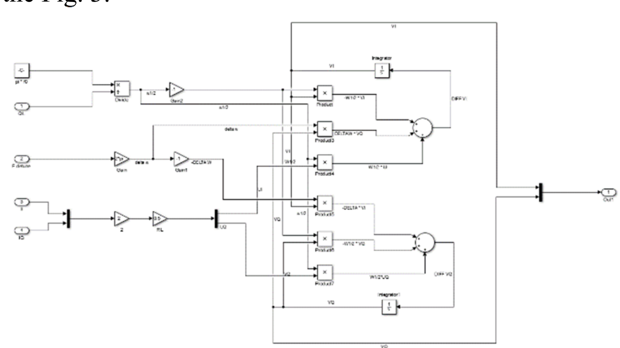
Figure 3: Simulation cavity block diagram.

In order to check the performance of simulation cavity, a square wave was used as input to pass through the simulation cavity. The amplitude of input waveform set to 4000, phase is 35.1° . Loaded quality factor of cavity is

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3840, and detune is 0. Testing result shown in the Fig. 4. And this output can be directly used as the reference input of llrf system.

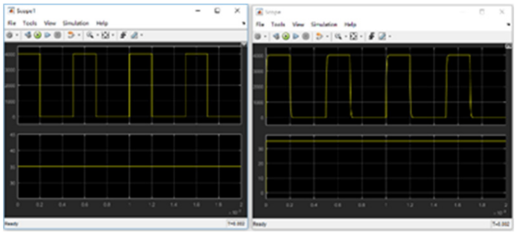

Figure 4: Input & output waveform of simulation cavity testing system.

In PI controller model, considering that all the operations of LLRF system are completed in a pulse, both the Proportions and integral terms should be multiplied by a set of unit pulse which period is the same with feed forward base model, reference model and beam loading model. Figure 5 is the architecture of PI controller model.

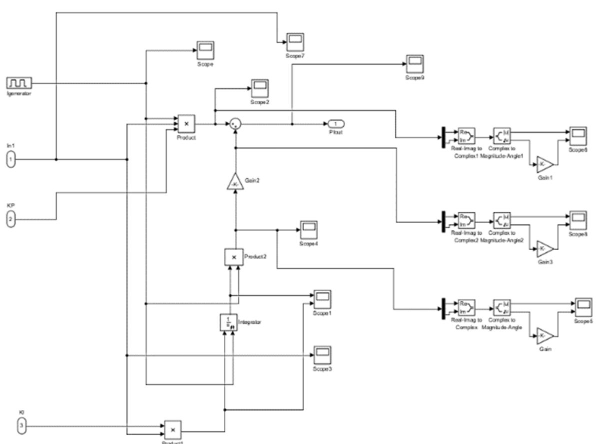

Figure 5: PI controller Simulink block diagram.

The other model that didn't mention above has almost the same architecture. Take Feed forward (FF) base model as an example. Pulse generator was used to produce a set of square wave and a constant model was used to generate phase value then convert these data to corresponding IQ component. The complete llrf system model was shown as Fig. 6. A transport delay model was add into the feedback loop. By adjusting the proportional and integral coefficient, we could use feedback control to compensate the beam loading effect. Figure 7 show the system output before and after choosing a fit proportional & integral coefficient (k_p &k_i) value. The experimental results are very similar to the actual situation in j-parc.

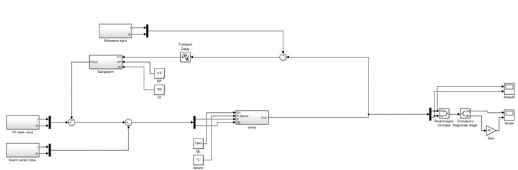

Figure 6: LLRF system block diagram.

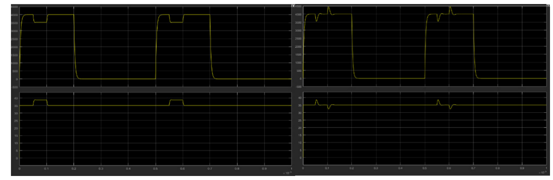

Figure 7: System output waveform before (left) and after (right) choosing a appropriate k_p & k_i.

ILC TEST ON LLRF SYSTEM MODEL

The architecture of ILC test is shown in Fig. 8. LLRF system as a plant is packaged in a subsystem module. The reference of ILC test system is same with the reference model of LLRF system.

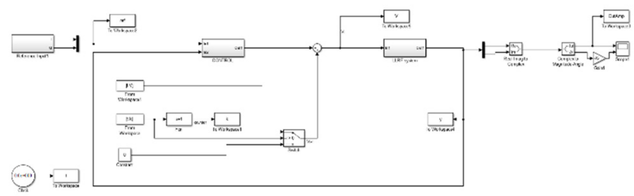

Figure 8. The block diagram of ILC test system.

Running result is shown in Fig. 9, left side picture is the reference & output waveforms when ILC didn't work, right side is the tracking waveforms of output after 40 iterations. The final output waveform is shown in the Fig. 10. Final output (green line) has almost overlapped with the reference waveform. And the monotonically decreasing error curve, shown in the Fig. 11, also proves that ILC works well.

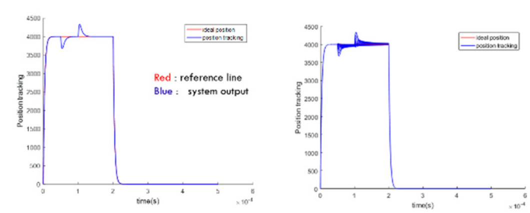

Figure 9: Trajectory tracking waveforms of 40 iterations.

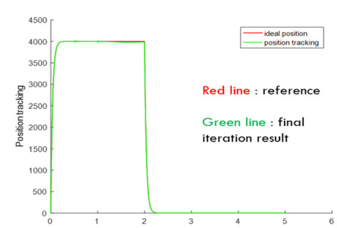

Figure 10: Comparison between final waveform and reference waveform.

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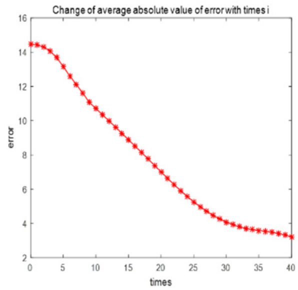

Figure 11: Relationship between iterative times and average value of the error of each iteration.

SUMMARY

In order to deal with the serious beam load effect in the future, an adaptive feedforward control methods which based on iterative learning control was put forward. For verifying its effectiveness, a LLRF system simulation model was built in Simulink. The ILC testing result was summarized. After using ILC control into the LLRF system, the beam loading effect is effectively suppressed. The simulation result shows that as long as the number of iterations is sufficient, the output waveform can be close to the ideal value.

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