PROGRESS IN THE WORK ON THE TUNER CONTROL SYSTEM OF THE CERL AT KEK

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Abstract

A compact energy recovery linac (cERL), which is a test machine for future 3 GeV ERL project, was constructed at KEK. Five superconducting (SC) cavities were installed in the injector and main linac of the cERL. The SC cavities in cERL are prone to detuning by disturbances such as microphonics. Therefore, a piezobased tuner system was used to compensate for the detuning of the SC cavity in the cERL. We have proposed advanced control methods that aim at improving the performance of the cERL tuner systems. In this paper, we present the progress in our work on the cERL tuner systems. The preliminary results of the beam commissioning are also presented.

INTRODUCTION

A 3 GeV energy recovery linac (ERL) light source is proposed in KEK. For the demonstration of the 3 GeV ERL project, a compact ERL (cERL) was constructed as a prototype machine [1, 2]. The cERL is a superconducting (SC) machine operated in the continuous-wave mode. Three two-cell SC cavities and two nine-cell SC cavities were installed in the injector and main linac (ML), respectively. To achieve the required beam quality, the radio frequency (RF) field and cavity resonance frequency must be regulated using low-level radio frequency (LLRF) feedback systems and tuner feedback systems, respectively.

As illustrated in Fig. 1, field programmable gate array (FPGA)-based digital LLRF and tuner systems were developed for the cERL [3, 4]. First, the 1.3 GHz RF signal from the SC cavity was down converted to the intermediate frequency (IF) signal in both these systems. The IF signals were then digitized by 16-bit ADCs and then processed by the FPGA. In the LLRF systems, the processed signals were finally used to drive a klystron, which drives the SC cavities. On the other hand, in the tuner system the processed signals were used to drive a piezo, which tunes the resonance frequency of the SC cavity.

Both the LLRF systems and tuner systems are prone to be disturbed by disturbances like microphonics. In principle, if we know the system model well, these disturbances can be re-constructed and then removed inside the FPGA. This control approach is named the disturbance observer (DOB)-based control. Since we were able to reject the microphonic and other disturbances of the RF field by the DOB control in the LLRF system of the cERL successfully [5-7], we try to apply this method to the cERL tuner system as well. In this paper, we first introduce the LLRF system in the cERL and then describe the principle, design, and implementation of the DOB-based approach. Finally, the preliminary results are used to compare the proposed DOB control and the previous PI control in the cERL beam commissioning.



Figure 1: Schematic of the digital LLRF and tuner systems of the cERL.

TUNER SYSTEM

Figure 2 shows the digital signal processing (DSP) algorithms of the cERL tuner control system inside the FPGA. After conversion to digital form by the 16-bit ADCs, the baseband in-phase and quadrature (I/Q)components of the cavity pick up signal and feedforward (P_{f}) signal are extracted. In the next stage, the I/O signals are filtered by a first order infinite impulse response (IIR) filter. The phase differences ($\Delta \theta$) between the pick-up signal and P_f signals are then calculated. For piezo feedback control, the phase difference errors are regulated by an integral (I) controller. For the mechanical tuner feedback control, pulses in the clockwise (CW) or counter-clockwise (CCW) directions are output in proportion to $\Delta \theta$. The piezo feedback is usually sufficient for the resonance frequency control in the SC cavities [4, 8].



Figure 2: DSP implementation of tuner feedback control system in the cERL.

IIR FILTER

To suppress the mechanical modes of the piezo system, the IIR filter with a difference equation as shown in (1), is applied in the tuner feedback system. It is a simple IIR filter with only one real pole. The filter bandwidth is proportional to the adjustable parameter α .

$$y(n) = \alpha \cdot x(n) + (1 - \alpha) \cdot y(n - 1), \ \alpha \ll 1$$
(1)

The realization of the IIR filter in the previous tuner system is shown in Fig. 3(a). This IIR filter works well if the filter bandwidth is large enough (e.g. $f_{BW} \ge 1$ kHz). However, in the low-bandwidth case, the finite word length (FWL) effects produce a significant degradation of the filtering characteristics. To decrease the FWL effects, we have to increase the bit sizes of the two 18×24 multipliers in Fig. 3(a). As a result, the DSP hardware resources inside FPGA also have to be increased. Since that type of IIR filters are widely used in the digital LLRF systems and tuner systems in cERL, it is worthwhile to optimize the structure of this filter.

After a simple transformation, the difference equation in (1) can be transformed to (2). The corresponding realization of (2) is presented in Fig. 3(b). It can be clearly observed that the proposed structure requires only one 24×36 multiplier. Therefore, additional DSP hardware resources are not necessary even if the bits of the multiplier are doubled.

$$y(n) = \alpha \cdot [x(n) - y(n-1)] + y(n-1), \ \alpha <<1$$
(2)



Figure 3: Realization of the previous (a) and proposed (b) IIR filter of the tuner system.

DOB CONTROL OF TUNER SYSTEM

DOB control is an advanced control approach that aims at rejecting the disturbances in a control system. Since there are various disturbances in both the LLRF and tuner systems, the DOB control can be a suitable approach for these control issues. We have already implemented the DOB-based control method in the LLRF system in the cERL commissioning successfully [5-7], hence, we would like to apply this method in the tuner system also. According to the basics of the DOB approach presented in [5-7], a nominal open-loop system model is required for the DOB control. The complete mathematical model (transfer function) of the tuner system is given in [9]

$$H(s) = \left(\frac{M_0}{\tau s + 1} + \sum_{k=1}^{N} \frac{\omega_k^2 M_k}{s^2 + 2\xi_k \omega_k s + \omega_k^2}\right) e^{-T_d s} .$$
 (3)

The parameter T_d outside the parentheses in (3) represents the measured group delay. The first-order components in the parentheses represent the passband of the tuner system, where M_0 is the steady state gain and τ a low-pass time constant. The second-order components are related to the high-frequency modes. Owing to the very tight time schedule in the cERL beam commissioning, we didn't have enough time to identify the detailed high-frequency modes of the tuner system, i.e., the coefficients of the second order component in (3). In this paper, we considered a tuner system of a first-order model with group delay that can be expressed by

$$H_n(s) = \frac{M_0}{\tau s + 1} e^{-T_d s}.$$
(4)

The coefficients in (4) were identified by exciting the tuner system with a square wave in the DAC output and measuring the response of the phase difference; $\Delta\theta$ (see Fig. 4). After simple data analysis, the parameters such as group delay and time constant were obtained.



Figure 4: Simple identification experiment for the model in (4). Some high-frequency modes around 340 Hz can be also observed.

Similar to DOB control of the LLRF system [5-7], the overall model of the DOB control and previous integral individual control of the tuner system is shown in Fig. 5. The presented DOB-based controller is indicated by the red dotted rectangle. The switch "SW" in Fig. 5 controls the enable/disable operation of the DOB controller, and the parameter G_{DOB} regulates the gain of the DOB controller. The IIR filter in Fig. 3 (b) is applied in the digital filters of $F_1(z)$, $F_{ADC}(z)$ and $F_{DAC}(z)$. The bandwidths of both $F_{ADC}(z)$ and $F_{DAC}(z)$ are more than 5 and kHz. The bandwidth of $F_1(z)$ was set to be 25 Hz to suppress the 50 Hz components in ML cavities [6]. The definition of each model is summarized in Table I. In principle, the real disturbances d in the tuner system can be estimated by the DOB controller output, d_e , therefore, after removing that d_e in the tuner feedback loops, we can improve the disturbance rejection characteristics of the system [5-7].



Figure 5: Overall model of "I+DOB" control, the DOB controller is indicated by the red dotted rectangles.

Table 1: Definition of the Models and Parameters in Fig. 5

Parameters	Definition
d(t)	Disturbance signal
$d_e(k)$	Estimated disturbance by DOB control
y(t)	Phase difference
n(t)	High frequency noise signal
Q(z)	Q-filter model, a second order IIR filter
$F_{1, ADC, DAC}(z)$	IIR filter presented in (2)
z^{-N}	Nominal group delay model
G_{DOB}	Gain of the DOB control (from 0 to 1)
I(z)	Integral controller
H(s)	Real open-loop model of tuner system
$H_n(z)$	Nominal open-loop model of tuner system (w/o group delay)

EXPERIMENT ON CERL BEAM COMMSSIONING

We developed a DOB-based controller in an FPGA and demonstrated its performance in the digital tuner system of the ML cavities. Models (parameters) of the controllers used in the experiments are given in (5), (6) and (7). At first, we tried to operate the tuner system with integral individual control (by switching off the "SW" in Fig. 5), and we measured the phase differences; $\Delta \theta$. In the next step, we switched on the DOB control, gradually raised the DOB gain G_{DOB} from 0 to 1, and then measured the phase differences again. With increase in the G_{DOB} , the disturbances in the phase differences reduced; however, when the gain was raised to 0.5, the components around 340 Hz is excited and system became unstable (see Fig. 4 and Fig. 7). The most probable reason is that there is a mechanical mode around 340 Hz, which is excited by the inverse components $H_n^{-1}(z)$ of the DOB controller (see Fig. 5).

$$H_n(s) = \frac{2.7}{0.0016 \cdot s + 1} e^{-0.0005 \cdot s}$$
(5)

 $\mathcal{Q}(s) = \left(\frac{2\pi \cdot 1000}{s + 2\pi \cdot 1000}\right)^2 \tag{6}$

$$I(s) = \frac{15.5}{s} \tag{7}$$

Figure 6 compares the measured phase differences (left: waveform, right: spectrum) of the integral individual control and "I+DOB" control. Here, the gain of the DOB control (G_{DOB}) is 0.4 (the highest value we could successfully reach). It can be observed that, the disturbance in the low frequency domain (DC to 100 Hz) are rejected well by the DOB controller.

Figure 7 shows the 340 Hz component excited in the case of $G_{DOB} = 0.5$. It seems that the simple first-order model in (4) is not sufficient to represent the behavior of a real tuner system; thus, higher precision system identification is necessary.



Figure 6: Integral individual control (blue) vs. "I+DOB" control (red). The waveform of phase difference (left) is plotted as well as its FFT analysis (right).



Figure 7: Tuner system becomes unstable in the case of $G_{DOB} = 0.5$. A component at approximately 340 Hz was excited.

SUMMARY

Digital LLRF systems and tuner systems were developed for the cERL. To decrease the influence of the FWL effects of the tuner system, we first optimized the structure of the IIR filter. Furthermore, to improve the disturbance rejection, we implemented a DOB-based control approach for the tuner system. Experiments in beam commissioning indicated that the DOB control was effective in rejecting the low-frequency disturbances. However, due to the probable existence of mechanical modes, the gain of the DOB controller was limited to less than 0.5. A higher-precision system model is required for further improvement in the system performance.

authors

REFERENCES

- [1] N. Nakamura et al., "Present status of the compact ERL at KEK," Proc. IPAC2014, Dresden, Germany (2014).
- [2] S. Sakanaka et al., "Construction and commissioning of compact-ERL Injector at KEK," Proc. ERL2013, Novosibirsk, Russia (2013).
- [3] T. Miura et al., "Performance of RF systems for compact ERL injector at KEK," Proc. ERL 2013, Novosibirsk, Russia (2013).
- [4] T. Miura et al., "Performance of RF system for compact-ERL main linac at KEK," Proc. IPAC'14, Dresden, Germany (2014).
- [5] F. Qiu et al., "A disturbance-observer-based controller for LLRF systems," Proc. IPAC'15, Richmond, USA (2015).
- [6] F. Qiu et al., "Performance of the digital LLRF systems at KEK cERL," Proc. ERL2015, New York, USA (2015).
- [7] F. Qiu et al., "Application of disturbance observerbased control in low-level radio-frequency system in a compact energy recovery linac at KEK," PRSTAB 18,092801(2015).
- [8] K. Enami et al., "Performance evaluation of ERL main linac tuner," Proc. IPAC'14, Dresden, Germany (2014).
- [9] A. Neumann et al., "Analysis of active compensation of microphonics in continue wave narrow-bandwidth superconducting cavities," PRSTAB 13, 082001 (2010).