Implementation of flat-top output pulse of RF pulse Compressor for SXFEL

Yiming Xu, Wencheng Fang, Chengcheng Xiao

xuym@sari.ac.cn; fangwc@sari.ac.cn; xiaocc@sari.ac.cn

LOW LEVEL RADIO FREQUENCY WORKSHOP 2023

LLRF2023

INTRODUCTION

- The RF pulse compressor is a critical kind of passive equipment for compressing the long low-power RF pulses to the short high-power RF pulses.
- SXFEL requires the output envelope of the C-band compressor become from the original (fig.1a) to the flat-top (fig.1b) by the LLRF control system, for supporting the multi-bunch modes of the EUV beamline.
- The adaptive control-based algorithm with complex multivariable estimation is used to generate and maintain the flat-top output, which regards the RF system as a first order model and evaluates its real-time transfer matrix through the input and output samples.
- The recursive least square method in complex form is raised, which reduces the algorithmic time and space complexity and avoids the data saturation.
- The optimum control function is raised, which considers the control accuracy and the change rate of input synthetically to obtain the desired control effect.
- The RF test and beam test at SXFEL demonstrate that the algorithm can generate the expected flat-top RF power pulse of the compressor as well as stabilize long-term amplitude and flatness against environmental variations.
- "Yiming Xu, et al., Design and verification of adaptive control to generate flat-top radio frequency power output of pulse compressor for SXFEL, Nucl. Instrum. Methods A 1031 (2022) 166596." shows the more details.

ADAPTIVE CONTROL WITH MULTIVARIABLE ESTIMATION

- The compressor's input, $U(k)$, and output, $Y(k)$, during the output period is described by two 11-sample sequences with 40 ns. Therefore, the system's mathematical model can be represented by

$$Y(k) = BU(k) + b + \Xi(k)$$

where $\Xi(k)$ is the white noise vector, b is the 11×1 offset vector and B is a 11×11 matrix. The parameters of B and b are complex and can describe the system totally. Moreover, B and b are computed numerically by the least square estimation from the real input and output of the RF system.

$$B(k) = Y\bar{U}^T(U\bar{U}^T)^{-1}(1)$$

- For reducing the algorithmic complexity, calculating Eq.1 can be replaced to calculating Eq.2-4 successively when a new sample is obtained.

$$P(k+1) = P(k)(I - uK(k+1))(2)$$

$$K(k+1) = \frac{\bar{u}^T P(k)}{1 + \bar{u}^T P(k) u}\ (3)$$

$$B(k+1) = B(k) + (y - B(k)u)K(k+1)(4)$$

where I is the identity matrix, and u and y is the latest input and output respectively. Consequently, the variables are updated in real time.

- It is hoped that both the control error and the change of the control point close to zero, so the cost function, J, is introduced.

$$J = \left(\overline{Y_r - BU - b}\right)^T G(Y_r - BU - b) + (\overline{U - U_0})^T Q(U - U_0)$$

where G and Q are the weight matrixes, and Y_r is the set point. U is calculated according to Eq.5 to minimize J.

$$U = (\bar{B}^T GB + Q)^{-1}(\bar{B}^T GY_r - \bar{B}^T Gb + QU_0)(5)$$

Consequently, the optimum control law is established.

- The algorithm flow is shown in table 1.

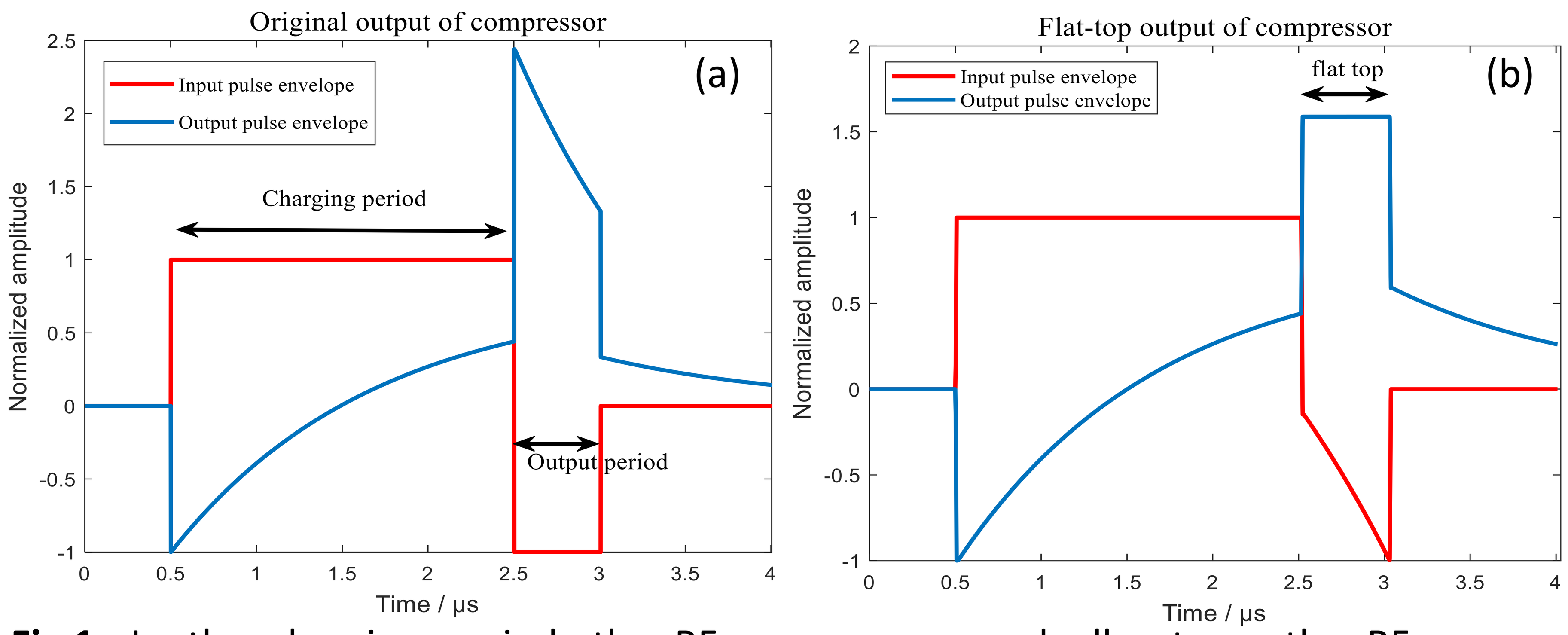

Fig.1: In the charging period, the RF compressor gradually stores the RF power. Subsequently, the output period begins when the phase of the input pulse reverses 180°. The flat top will be got if the input pulse is modulated accurately.

Table 1: Algorithm flow to generate and maintain the flat-top pulse

(i)	Initialize the intermediate parameters, $B(k)$ and $P(k)$. They could be the stored value, or O and $10^9 I$ simply.
(ii)	Record the real output U(k) of LLRF system and measure the output Y(k) of the compressor.
(iii)	Calculate the P, K and B following Eq.2-4 to modify the real-time error.
(iv)	Calculate the optimum control law, U(k + 1), following Eq.5.
(v)	Output U(k + 1) to the compressor system, then back to step (ii).

RF & BEAM EXPERIMENT

- A MTCA-based LLRF with the analog and digital boards is used to sample and generate the C-band pulse. The Python's libraries, Pyepics and PyDM, and EPICS are used to conversate with FPGA, display the waveforms and change the feedforward table in real time.
- Fig.2 shows the RF pulse amplitude and phase at the output period. The amplitude flatness is 0.1%, and the phase flatness is 0.1°, which satisfies the SXFEL's requirement.
- Fig.3 shows the dynamic behavior of the control algorithm. The set point was manually changed several times. The algorithm can always adjusts the LLRF output to recover the flat top to the required point and flatness within 50 iterative calculations.
- The beam experiment was verified at SXFEL. The beam energy was measured when the triggers of the RF pulses were changed while the triggers of the bunches were fixed to ensure whether the beams at different positions experienced the same accelerating gradient. The flatness of bunches' energy in flat top is 0.8%. Peak-to-peak energy is 2.2 MeV.

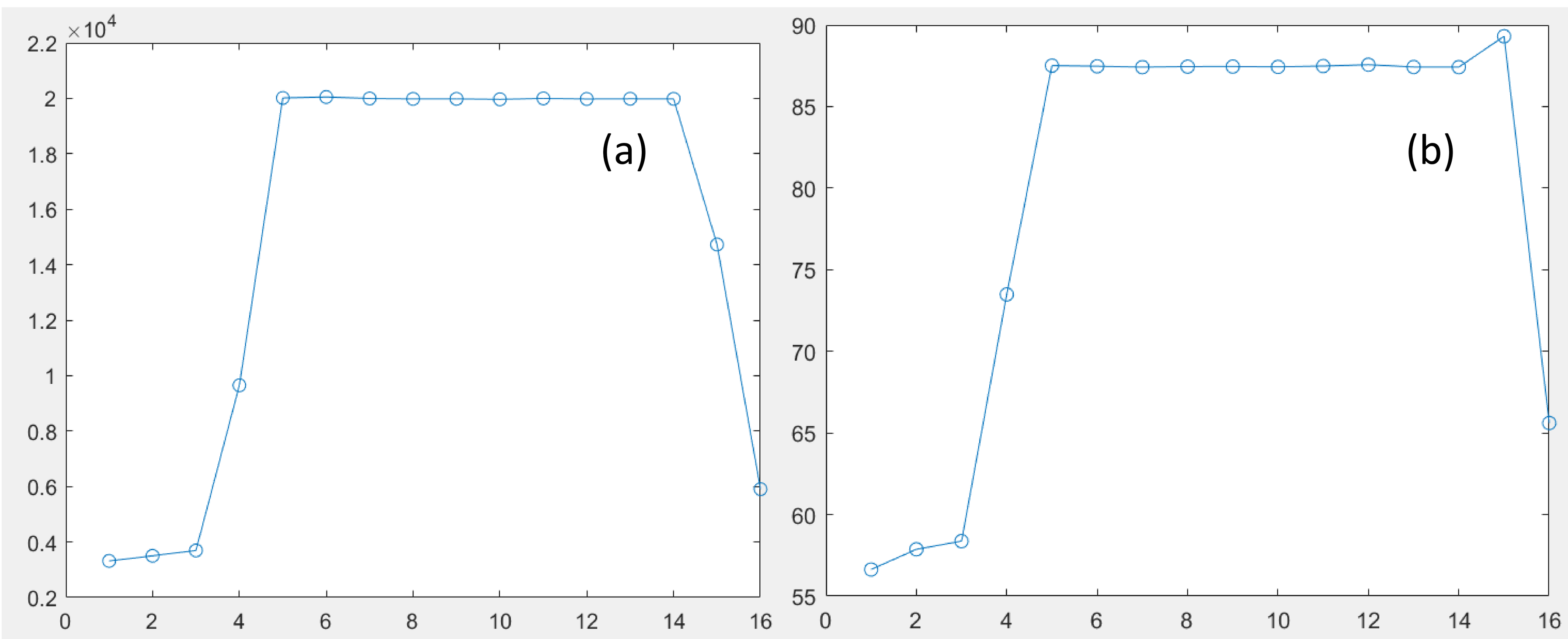

Fig.2: The RF waveforms about a single pulse are shown. (a) and (b) are the amplitude and phase of the flat-top output of compressor respectively. There are 10 samples in the flat top, and their stand deviation represents the flatness.

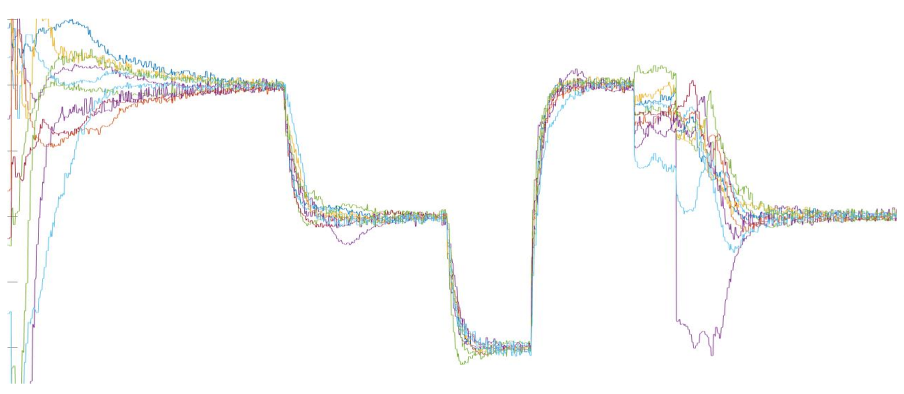

Fig.3: The amplitude of the 10 samples with the flat top changed over time, during which the set amplitude and phase were manually changed 5 times.

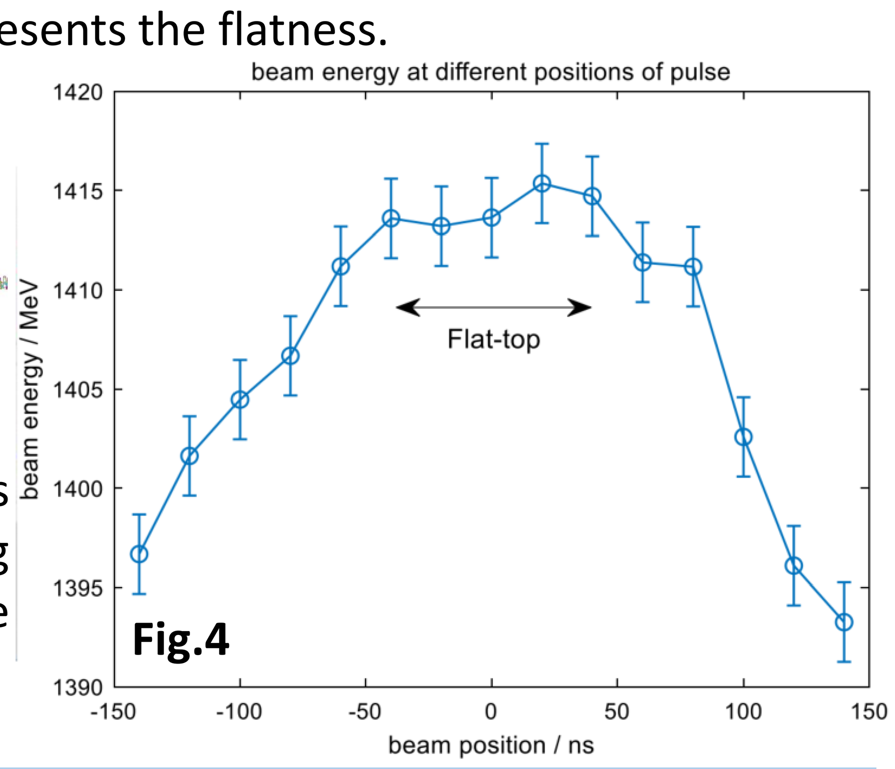

Fig.4

CONCLUSION

- A serial of complex sequence can describes the amplitude and phase of a waveform simultaneously.
- The adaptive control-based algorithm has been designed, implemented, and validated in SXFEL. The results demonstrate that the algorithm can generate the expected flat-top RF power pulse of the compressor as well as stabilize long-term amplitude and flatness against environmental variations.
- The algorithm has a larger convergence domain and a faster convergence rate, and is universal in that it is unaffected by specific system parameters.
- Such method is very appropriate for the large facility with lots of compressor, because it is Insensitive to the slow drift and manufacturing.