RF Pulse Flattening in the SwissFEL Test Facility based on Model-free Iterative Learning Control

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Abstract

This poster introduces an iterative approach to producing flat-topped radio frequency (RF) pulses for driving the pulsed linear accelerators in the SwissFEL. The method is based on model-free Iterative Learning Control (ILC) which iteratively updates the input pulse shape in order to generate the desired amplitude and phase pulses at the output of the RF system.

Iterative Learning Control is a method for controlling systems that operate in a repetitive, or trial-to-trial mode. In this method, the measured trajectory is compared to the desired trajectory to give an error estimate which is then used to update the input for the next trial. A new version of ILC has been recently developed which is not based on the model of the system and thus the usual system identification procedure is not required.

The recent method has been modified and successfully tested on the klystron output in a C-band RF station of the SwissFEL facility to improve the flatness of the amplitude and phase pulse profiles.

RF Station Layout

The RF and low-level RF layout of the SwissFEL C-band station is illustrated in Fig. 1. The discrete waveforms of the in-phase, I, and quadrature, Q, components of the RF signal are fed into the vector modulator to be up-converted to the carrier frequency (5.712GHz). Each waveform contains 2048 samples with the sampling time of Ts = 4.2 ns. The RF signal drives the klystron which delivers high power RF at the output. In C-band stations, a pulse compressor (BOC) is placed after the klystron, followed by four accelerating structures.

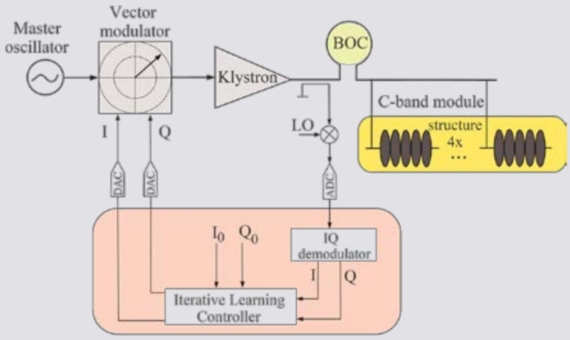

Figure 1: The RF layout of the SwissFEL C-band station.

● Objective: Modifying the input RF waveforms to the klystron in order to generate flat-topped pulse at the output.

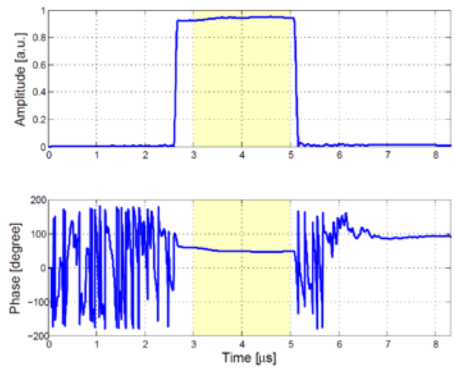

Figure 2: A typical RF pulse generated by the klystron.

The electron-bunches are fired after filling time of the structures somewhere in the colored area in Fig. 2, which we refer it to as the flat-topped region. The amplitude is normalized with respect to the saturation level (with 5% headroom).

Iterative Learning Control

The Iterative Learning Control is a technique to manipulate the input pulse shape iteratively until the output pulse shape fulfils the requirement. Model-free ILC methods are rarely investigated in literature, in contrast to variety of model-based methods. Model-free ILC algorithms have the advantage that no system identification experiments are required.

For the notation, subscript "i" denotes the iteration counter, whereas index k captures the discrete time instants within one RF pulse. The following input update law is considered for an LTI SISO system,

$$u_{i+1}(k) = u_i(k) + u_{lc}(k) * \alpha_i(k), \qquad (1)$$

where $u_i(k) \in \mathbb{R}, k \in \{1, 2, \dots, N\}$, and $u_{lc}(k)$ denotes any linear combination of the previous trials' input signals $u_0(k), u_1(k), \dots, u_i(k)$, and where $\alpha_i(k)$ is a trial-varying but LTI FIR filter of length N.

Since the system is assumed to be LTI, the corresponding output $y_{i+1}(k)$ is predicted to be

$$\hat{y}_{i+1}(k) = y_i(k) + y_{lc}(k) * \alpha_i(k), \qquad (2)$$

where $y_{lc}(k)$ represents the corresponding linear combination of the previous trials' output signals $y_0(k), y_1(k), \dots, y_i(k)$, and $\hat{y}_{i+1}(k)$ is the prediction of the output of trial i+1 for input $u_{i+1}(k)$ without using the system model.

Learning Algorithm

- At iteration 0, small steps $u_{0I}(k)$ and $u_{0Q}(k)$ are applied to the I and Q channels of the vector modulator, respectively, and the resulting $y_{0I}(k)$ and $y_{0Q}(k)$ are measured.
- At iteration "i", the following matrices are calculated:

$$U_{lc} = U_i - U_{i-1} + \gamma U_0,$$
$$Y_{lc} = Y_i - Y_{i-1} + \gamma Y_0,$$

where,

$$U_{lc} = \begin{pmatrix} U_{lcI} & U_{lcQ} & 0 & 0 \\ 0 & 0 & U_{lcI} & U_{lcQ} \end{pmatrix}, \quad Y_{lc} = \begin{pmatrix} Y_{lcI} & Y_{lcQ} & 0 & 0 \\ 0 & 0 & Y_{lcI} & Y_{lcQ} \end{pmatrix},$$

with U_i, U_0, U_{lcI} and U_{lcQ} denoting the lower-triangular Toeplitz matrices of $u_i(k)$, $u_0(k)$, $u_{lcI}(k)$ and $u_{lcQ}(k)$, respectively, and γ is a tuning factor. Similar definitions apply for Y_i, Y_0, Y_{lcI} and Y_{lcQ} .

- The optimal LTI filter α_i is determined as follows,

$$\tilde{\alpha}_i^* = (rI + Y_{lc}^T Y_{lc})^{-1} Y_{lc}^T (y_i - y_d).$$

where "r" is the weight on the input changes, and y_i and y_d are the measured and desired output vectors, respectively.

$$y_d := \begin{pmatrix} y_{dI} \\ y_{dQ} \end{pmatrix}$$

- The input waveforms of the next pulse are updated as,

$$u_{i+1} = u_i + U_{lc}\tilde{\alpha}_i^*,$$

where u_i captures both I and Q inputs,

$$u_i := \begin{pmatrix} u_{Ii} \\ u_{Qi} \end{pmatrix}, \quad u_{Ii}, u_{Qi} \in \mathbb{R}^N,$$

- The input waveforms are applied to the vector modulator (with defined bounds on the inputs), and the process repeats until convergence.

Experimental Results

The actuation and measurement are based on I and Q waveforms, however we are mostly interested in amplitude and phase due to their physical meaning. The algorithm begins with slightly exciting the input I and Q channels by small steps u_{I0} and u_{Q0}, respectively.

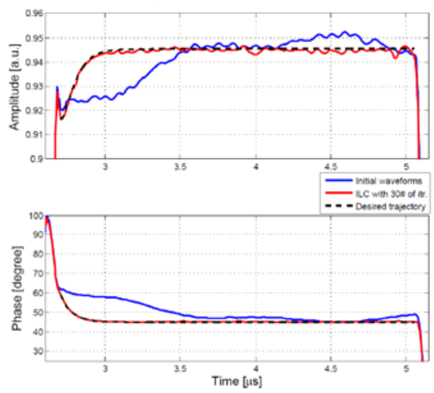

Figure 3: The klystron output amplitude and phase waveforms after 30 iterations (in red). The blue signal denotes the initial output waveforms (iteration #0).

Figure 3 shows the RF amplitude and phase waveforms after 30 iterations compared to the initial waveforms. The variance of the pulse over the flat-topped region is used as a measure of flatness. Figure 4 illustrates the standard deviation of the amplitude and phase pulses as the iteration advances. The iteration number "0" corresponds to the initial waveforms. The flatness has been improved by a factor of 3 and 5 for the amplitude and phase pulse, respectively. After around 20 iterations, the tracking error converges to the residual error which comes from the pulse to pulse noise through the system. The corresponding generated input waveforms are depicted in Fig. 5. As we can see, the resulting input signal is different from the nominal rectangular pulse.

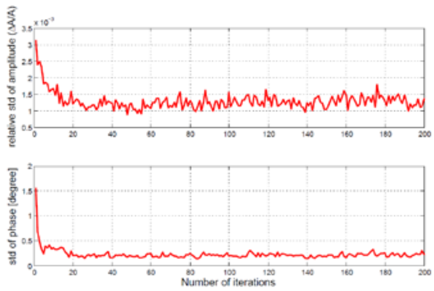

Figure 4: The standard deviation of flat-top amplitude and phase versus number of iterations.

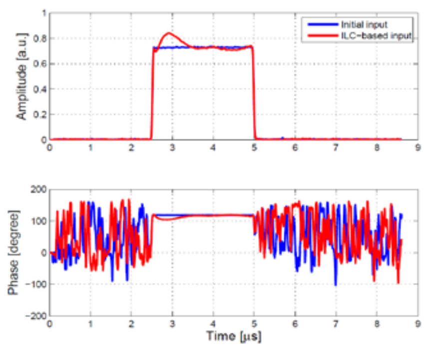

Figure 5: The input amplitude and phase waveforms generated by ILC (in red). The blue signal denotes the initial input waveforms (iteration #0).

Summary

For multi-bunch operation of a pulsed mode FEL, in which several electron bunches are accelerated within an RF pulse, it is often required that the amplitude and phase seen by the beam remain constant over the pulse length so that the bunches achieve the same energy level. For pulsed mode machines, like the SwissFEL, where the pulse length is relatively short and no intra-pulse digital feedback is feasible, iterative learning control is applicable to achieving the control objectives. In this poster, we investigated a model-free ILC approach and its application in RF pulse flattening of the klystron output. The proposed algorithm is applicable to RF waveform control in the other parts of the system.