ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA58

ITERATIVE TUNING OF THE BEAM FEEDFORWARD CONTROLLER FOR LANSCE LINAC DIGITAL LOW LEVEL RF CONTROL SYSTEM*

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Abstract

This paper addresses an iterative particle beam phase and amplitude feedforward controller tuning method based on the gradient search approach. The method does not need an a priori plant model as it only needs data collected in previous experimental runs. The controller is implemented on a field programmable gate array (FPGA) equipped with a real-time operating system and a network connection. Data from each RF pulse is collected and sent via the network to the FPGA for processing. The controller tuning is performed between the RF pulses. Once the tuning is performed, the controller parameters are downloaded to the controller in the FPGA and new controller parameters are applied at the upcoming RF pulse.

INTRODUCTION

The capabilities of the Los Alamos Neutron Science Center (LANSCE) experimental facilities include: 1) the Lujan Center, which requires short, high-intensity proton bunches in order to create short bursts of moderated neutrons with energies in the meV to keV range; 2) the Proton Radiography (pRad) Facility, which provides time-lapse images of dynamic phenomena in bulk material (for example, shock wave propagation) via 50-ns-wide proton bursts, repeated at time intervals as short as 358 ns with programmable burst repetition rates; 3) the Weapons Neutron Research (WNR) Facility, which provides unmoderated neutrons with energies in the keV to MeV range; 4) the Isotope Production Facility (IPF), which uses the 100-MeV H^+ beam to make medical radioisotopes; and 5) the Ultra Cold Neutron (UCN) Facility, which creates neutrons with energies below the μeV energy range for basic physics research [1]. The ability of the digital low-level RF (DLLRF) control system to accommodate various beam loading conditions is crucial for successful LANSCE operations in which a wide variety of beam types of various levels of beam loading are present in the accelerator's RF cavities. To minimize the perturbation of the cavity field caused by beam loading, the LANSCE DLLRF control system implements both a proportional-integral (PI) feedback controller (FBC) and feedforward controller capabilities (Fig. 1). For a small peak current beam loading, the PI FBC is sufficient to compensate for the beam loading in the cavity field. However, for high peak current beam loading, the simple PI FBC is not sufficient and a feedforward controller is crucial to the beam loading compensation capability. In this paper, a network based self-tuning method of the beam feedforward controller, an iterative feedforward controller tuning is proposed. The proposed iterative controller tuning uses collected data through the network and the controller gains are updated iteratively via gradient search of the cost function.

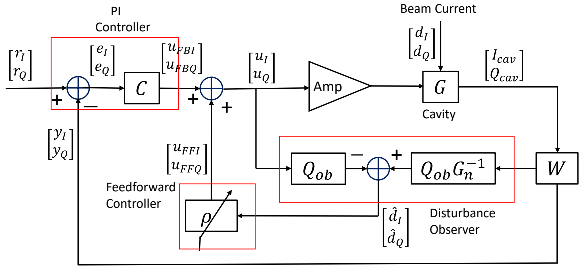

Figure 1: High-level functional diagram of the LANSCE digital low-level RF control system.

DECOUPLING CONTROLLER

The accelerator RF cavities are modelled as two-input-two-output (TITO) systems. When the detuning $\Delta\omega$ of the cavity is zero, the nominal plant function $G_n(s)$ is,

$$G_n(s) = \frac{h}{\tau_p s+1}\begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix}. \tag{1}$$

where τ_p is the time constant of the cavity, h is the steady state loop gain, s is the Laplace operator, $j\omega$, and θ is the phase shift of the loop. A simple intuitive approach to control the TITO multivariate system is described as a two-step procedure where a multivariate decoupling controller is designed to minimize with the off-diagonal cross-talk in $G_n(s)$, and then two, single-input single-output (SISO) controllers are designed and applied to each channel of the TITO system. A decoupling controller of the TITO system is a post-compensator, $W(s)$ that produces a newly shaped plant function $G_p(s)$ in which the off-diagonal terms are zero and the gain is unity,

$$G_p(s) = W(s)G_n(s) = \frac{1}{T_p s + 1}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{2}$$

The post-compensator $W(s)$ satisfying (2) is,

$$W(s) = \frac{1}{h}\begin{bmatrix} cos(-\theta) & -sin(-\theta) \\ sin(-\theta) & cos(-\theta) \end{bmatrix} \tag{3}$$

GRADIENT SEARCH METHOD APPLICATION FOR THE FEEDFORWARD CONTROLLER TUNING

From the view of the cavity field, the beam is an input disturbance. For small-current beam loading, a PI FBC is enough to compensate for the beam loading. For the high-current beam loading situation, in order to compensate for

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the beam loading effect on the cavity field, the feedforward controller is widely used.

Consider the cavity field control system model given by

$$\begin{bmatrix} y_I(t) \\ y_Q(t) \end{bmatrix} = G_p(s)\left\{\begin{bmatrix} u_{FBI}(t) \\ u_{FBQ}(t) \end{bmatrix} + \begin{bmatrix} u_{FFI}(t) \\ u_{FFQ}(t) \end{bmatrix} + \begin{bmatrix} d_I(t) \\ d_Q(t) \end{bmatrix}\right\} \quad (4)$$

where $y_I(t), y_Q(t)$ represent the complex cavity field, $u_{FBI}(t), u_{FBQ}(t)$ are the complex feedback controller outputs, $u_{FFI}(t), u_{FFQ}(t)$ are the complex feedforward controller outputs, and $d_I(t), d_Q(t)$ are the unknown complex beam currents. In the implementation of the feedforward controller for beam loading compensation, as shown in (4), the beam loading and the drive input to the cavity are input matched and the dynamics of the beam loading are identical to the cavity field dynamics. The delay of the beam loading response is unknown, and it is uncertain that the perfect feedforward controller is realized [2]. Hence, in the LANSCE DLLRF control system, the static feedforward controller is implemented as,

$$C_{ff}(s) = \begin{bmatrix} \rho_I & 0 \\ 0 & \rho_Q \end{bmatrix} \quad (5)$$

Using (5), the feedforward controller output is written as

$$u_{FF}(t) = \begin{bmatrix} \rho_I \, \hat{d}_I(t) \\ \rho_Q \hat{d}_Q(t) \end{bmatrix} \quad (6)$$

In (6), the estimates $\hat{d}_I(t)$ and $\hat{d}_Q(t)$ of the complex beam current components, $d_I(t)$ and $d_Q(t)$ are used because $d_I(t)$ and $d_Q(t)$ are unknown. A Disturbance Observer (DOB) [2] given by (7) is implemented in the DLLRF FPGA to estimate $\hat{d}_I(t)$ and $\hat{d}_Q(t)$ of $d_I(t)$ and $d_Q(t)$ in real time.

$$\begin{bmatrix} \hat{d}_I(t) \\ \hat{d}_Q(t) \end{bmatrix} = Q_{ob}(s)\, G_p^{-1}(s) \begin{bmatrix} y_I(t) \\ y_Q(t) \end{bmatrix} - Q_{ob}(s) \begin{bmatrix} u_I(t) \\ u_Q(t) \end{bmatrix} \quad (7)$$

where $u_I(t), u_Q(t)$ are complex plant inputs and $Q_{ob}(s)$ is a low-pass filter that yields $Q_{ob}(s)G_p^{-1}(s)$ causal.

The objective of feedforward controller tuning is to find the optimal value ρ^* of the parameter $\rho = [\rho_I \quad \rho_Q]^T$ that minimizes the cost function defined *J(ρ)* defined as,

$$J(\rho) = \frac{1}{2N}\sum_{i=1}^{N}\left(e_I^2(i) + e_Q^2(i)\right) \quad (8)$$

where $e_I(i)$ and $e_Q(i)$ are the complex error components. This feedforward controller gain tuning problem is solved iteratively using a gradient search algorithm

$$\rho^{(k+1)} = \rho^{(k)} - \alpha\, R^{-1}\, \nabla J\left[\rho^{(k)}\right] \quad (9)$$

where α is a scalar parameter to control the step size, $\rho^{(k)}$ is the parameter estimate in the k^{th} iteration, R is a matrix to modify the search direction, and $\nabla J\left[\rho^{(k)}\right]$ is the gradient of the cost function $J(\rho)$ with respect to the controller parameters $\rho^{(k)}$ of the k^{th} iteration, which is obtained by

$$\nabla J\left[\rho^{(k)}\right] = \frac{\partial J}{\partial \rho}\left[\rho^{(k)}\right] = \begin{Bmatrix} \frac{\partial J}{\partial \rho_I}\left[\rho^{(k)}\right] \\ \frac{\partial J}{\partial \rho_Q}\left[\rho^{(k)}\right] \end{Bmatrix} \quad (10)$$

$$\frac{\partial J}{\partial \rho_I} = \frac{-1}{N}\sum_{i=1}^{N} e_I(i)\, \frac{\partial y_I(i)}{\partial u_I}\, \hat{d}_I(i) \quad (11)$$

$$\frac{\partial J}{\partial \rho_Q} = \frac{-1}{N}\sum_{i=1}^{N} e_Q(i)\, \frac{\partial y_Q(i)}{\partial u_Q(i)}\, \hat{d}_Q(i) \quad (12)$$

In (11) and (12), $\frac{\partial y_I(i)}{\partial u_I}$ and $\frac{\partial y_Q(i)}{\partial u_Q(i)}$ are to be calculated. However, in our system, as a result of the decoupling controller $W(s)$, both are unity.

LOW-POWER TEST STAND EXPERIMENTS

The new algorithm has been developed and applied to tune the feedforward controller of the low-power test stand where an 805-MHz single-cell test cavity of 40-kHz single-sided 3-dB bandwidth is driven at 1 W. A simulated beam current having the same beam loading ratio as that of the LANSCE accelerator cavities is generated by an arbitrary function generator. The estimates $\hat{d}_I(t)$ and $\hat{d}_Q(t)$ and the errors $e_I(t)$ and $e_Q(t)$ are uploaded to the LANSCE Control System (LCS) server through the LCS network. The computation of the controller parameters at the LCS server and subsequent downloading to DLLRF system are achieved between RF pulses until the tuning algorithm satisfies a stop criterion. Figure 2 shows the low-power experimental results. Figure 2(a) shows that the iterative tuning algorithm converges in fewer than 18 iterations yielding large improvements in amplitude and phase errors shown in Fig. 2(c, d). Figure 2(b) shows that the phase of the controller parameters does not change substantially, which implies that the decoupling controller achieves the decoupling of the off-diagonal cross-talk well.

ITERATIVE FEEDFORWARD CONTROLLER TUNING FOR THE LANSCE PROTON BEAM

The proposed iterative feedforward controller tuning algorithm is applied for 805-MHz coupled cavity linac (CCL). It is noted that since the linac is producing an H$^-$ proton beam for the users, the feedforward controller parameters were coarsely tuned so that the amplitude error and the phase error are within the error requirements, ±1.0% amplitude error and ±1.0 °phase error before the proposed feedforward controller tuning algorithm is applied for fine tuning. In our DOB design, a second-order low-pass filter is chosen as the DOB filter $Q_{ob}(s)$.

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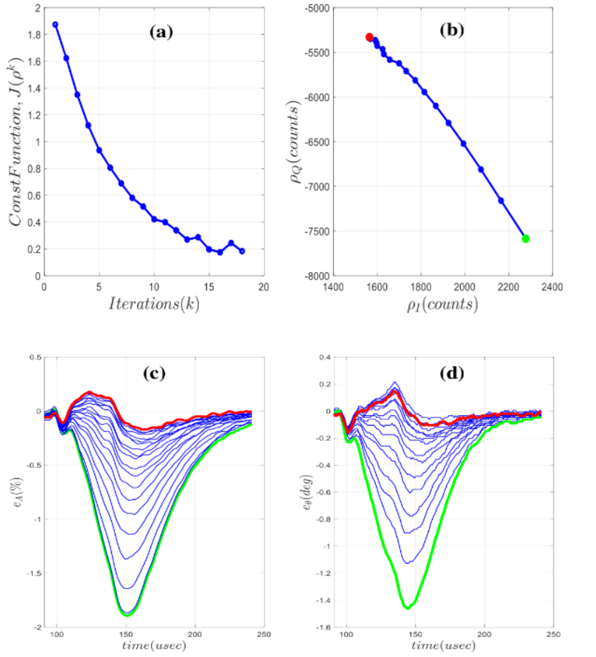

Figure 2: Low power test stand experiment: (a) Cost function; (b) Controller parameters;(c) Amplitude error; (d) Phase error;. In the (b), (c), and (d), the green line (dot) show the initial values and red lines (dot) show the final values.

Since the LANSCE H$^-$ beam has 30-us ramp-up time, the 3dB bandwidth of the disturbance observer filter $Q_{ob}(s)$ is determined considering by the frequency spectrum of the beam current. In the realization of DOB, 3dB bandwidths of the nominal plant $G_n(s)$ and the disturbance observer filter $Q_{ob}(s)$ are variable and are programmed through the LANSCE control system. Figure 3(a) shows the estimates $\hat{d}_I(t)$ and $\hat{d}_Q(t)$ of the I/Q components of the beam currents. Here, the 625-us-long beam is loaded at 90 us and DOB is enabled during the beam loading period. Figure 3(b) shows the cost function and Fig. 3(c) shows the controller parameters. It is observed that (i) the cost function is fluctuating slightly but the overall trend of it is monotonically decreasing, and after the 23rd iteration, it has converged; (ii) the controller parameters change drastically from the initial values (green dot) to the optimal values (red dot). Figure 3(d, e) show the 350-µs-long amplitude error e_A and phase error e_θ that cover the beam loading transient period. It is observed that the amplitude and phase errors improved significantly from the initial trajectories (green lines) to the final trajectories (red lines).

SUMMARY

In this paper, an iterative feedforward controller tuning algorithm has been discussed. The performance of the proposed algorithm has been verified using an 805-MHz low-power test stand. The tests show significant improvement of the beam amplitude and phase errors during beam loading of the cavity field. The proposed iterative tuning algorithm is then applied for the fine tuning of the feedforward controller operating on the LANSCE proton beam, showing significant improvement in the amplitude and phase errors of the cavity field. Since the tuning algorithm is based on a distributed, network-connected topology, the feedforward controller tuning parameters for multiple cavities are readily calculated and applied concurrently to improve the linac performance.

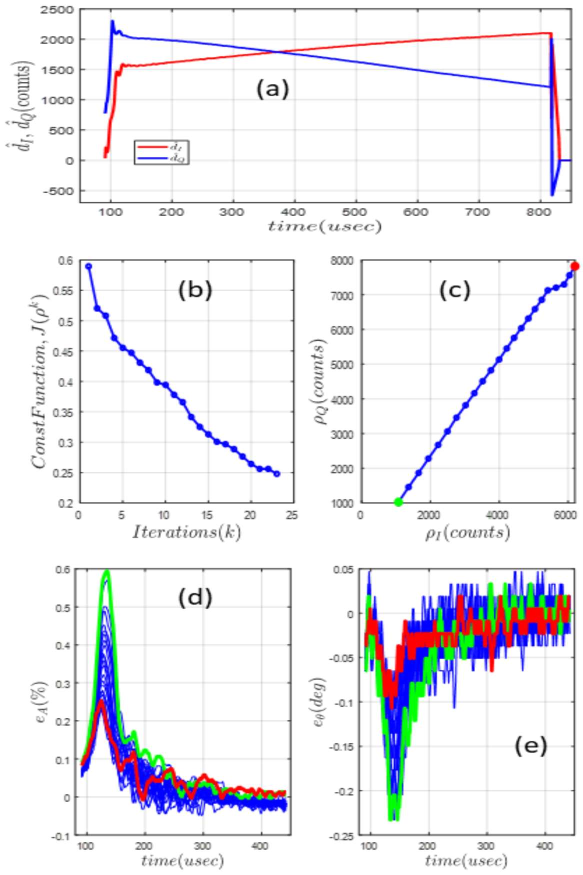

Figure 3: Performance results of the Iterative Tuning method: (a) Complex beam current estimates; (b) Cost function; (c) Controller parameters; (d) Amplitude error; and (e) Phase error.

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