

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

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I. Overall Control System Block Diagram

PI feedback Controller, $C(s)$, Static Beam Feedforward Controller(SBFFC) and Disturbance Observer are implemented. PI feedback Controller is the default controller and SBFFC is the enhancement. Disturbance Observer is implemented to estimate the complex beam currents. d_A is the beam current working as if it is the extraneous disturbance to the plant, RF cavity.

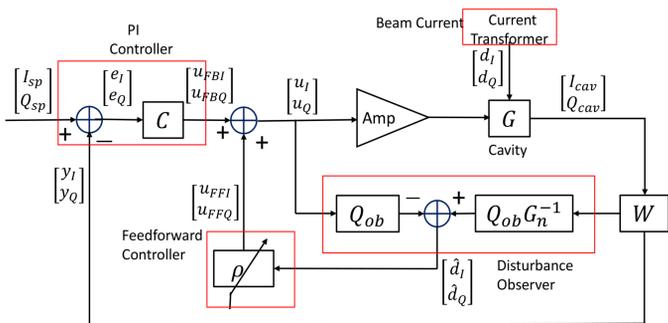


Figure 1. Overall Control System

II. Baseband RF System Model

The accelerator RF cavity is modelled as two-input-two-output (TITO) system. The high power RF amplifier at an operating In-phase(I) and Quadrature(Q) points can be modelled with a gain and two-by-two phase rotation matrix. The cavity RF pickup loop also can be modelled with a gain and two-by-two phase rotation matrix. Hence, overall RF system can be described as $G_n(s)$.

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

h : Steady State Loop Gain

τ_p : Time Constant

θ : Overall Loop Phase Rotation

III. Decoupling Controller

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 the LANSCE Digital LLRF system, an adaptive gain and phase calibration is implemented on the LLRF FPGA for the decoupling controller.

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

Decoupled System: $G_p(s) = W(s)G_n(s) = \frac{1}{\tau_p s + 1} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

III. PI Feedback Controller

Discrete-Time PI Controller: $C_D(z) = \frac{K_p}{2^{13}} + \frac{K_i}{2^{15}} \frac{1}{1-z^{-1}}$

Continuous-Time PI Controller: $C(s) = \left(\frac{K_p}{2^{13}} + \frac{K_i}{2^{15}} \right) + \frac{K_i}{2^{15} \cdot t_s} \frac{1}{s}$

IV. Disturbance Observer(DOB)

Beam Loaded Plant: $\begin{bmatrix} y_I(t) \\ y_Q(t) \end{bmatrix} = G_p(s) \left\{ \begin{bmatrix} u_I(t) \\ u_Q(t) \end{bmatrix} + \begin{bmatrix} d_I(t) \\ d_Q(t) \end{bmatrix} \right\}$

Beam Current Estimate by DOB:

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

Proper to suppress the non-repetitive disturbances at low frequency. The DOB needs the inverse model of the plant. In general, the plant, the base-band representation of the cavity is a lowpass filter characteristics and so the inverse of the plant is anti-causal, which means the implementation of the inverse of the nominal model, G_p^{-1} on the FCM is impossible. Then, instead of G_p^{-1} , $Q_{ob}G_p^{-1}$ is implemented with the design of the disturbance observer Q -filter. It is obvious that the filter, $Q_{ob}(s)$ plays a central role in the disturbance observer. Ideally, to estimate the effect of the disturbance, $Q_{ob}(s)$ should be designed to close to 1 in all of the frequency range. However, this may amplify the high frequency sensor/detector noise. Since the plant has lowpass filter characteristics, $Q_{ob}(s)$ is designed as a lowpass filter with its relative degree being equal or greater than the relative degree of the plant (model), G_p , so that $Q_{ob}G_p^{-1}$ is implementable. The reason that $Q_{ob}(s)$ is a lowpass filter is that the disturbance, $d_I(t), d_Q(t)$ are of low frequency or medium frequency and the sensor/detector noise is usually of high frequency. As a result, the disturbance observer estimates the disturbance of low frequency or medium frequency but rejects sensor/detector noise of high frequency. The cutoff frequency of $Q_{ob}(s)$ is vital in trading off between the stability and the performance, frequency characteristics of the disturbance, $d_I(t), d_Q(t)$ and the frequency characteristics of sensor/detector noise, etc.. Higher cutoff frequency yields better disturbance attenuation but it increases the sensitivity to the sensor noise.

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.

IV. Static Beam Feedforward Control(SBFFC)

The complex beam currents $d_I(t), d_Q(t)$ are scaled by controller parameters and added to the feedback Controller's complex outputs. $d_I(t), d_Q(t)$ are the unknown and they are estimated by the DOB. The controller parameters are iteratively tuned by the proposed method. In the implementation of the feedforward controller for beam loading compensation, the beam loading and the drive input to the cavity are input matched.

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

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

SBFFC Output: $u_{FF}(t) = \begin{bmatrix} u_{FFI}(t) \\ u_{FFQ}(t) \end{bmatrix} = \begin{bmatrix} \rho_I \hat{d}_I(t) \\ \rho_Q \hat{d}_Q(t) \end{bmatrix}$

V. Gradient Search Algorithm Application for the Iterative Feedforward Controller Tuning

The objective of feedforward controller tuning is to find the optimal value ρ^* of the parameter $\rho = [\rho_I \ \rho_Q]^T$ that minimizes the cost function and it is solved iteratively using a Gradient Search Algorithm. Necessary data upload, computation, controller parameter update, controller parameter downloading are performed between RF pulses.

Cost Function: $J(\rho) = \frac{1}{2N} \sum_{i=1}^N [e_I^2(i) + e_Q^2(i)]$

Errors: $\begin{bmatrix} e_I(i) \\ e_Q(i) \end{bmatrix} = \begin{bmatrix} r_I(i) \\ r_Q(i) \end{bmatrix} - \begin{bmatrix} y_I(i) \\ y_Q(i) \end{bmatrix}$

Parameter Update Rule:

$$\rho^{(k+1)} = \rho^{(k)} - \alpha R^{-1} \nabla J[\rho^{(k)}]$$

$$\nabla J[\rho^{(k)}] = \frac{\partial J}{\partial \rho} [\rho^{(k)}] = \begin{bmatrix} \frac{\partial J}{\partial \rho_I} [\rho^{(k)}] \\ \frac{\partial J}{\partial \rho_Q} [\rho^{(k)}] \end{bmatrix}$$

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

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

Iterative Feedforward Controller Tuning Application to 1W Test Stand System of Single cell cavity.

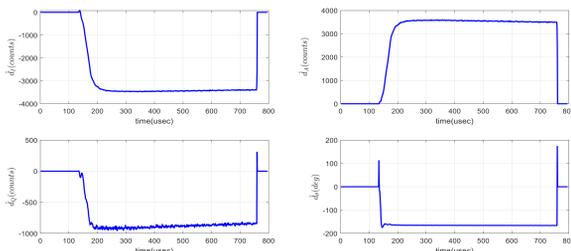


Figure 2. Low power test stand experiment. Left Column: Estimates \hat{d}_I, \hat{d}_Q of the complex Beam Currents; right column) Amplitude and Phase Estimates of Beam current.

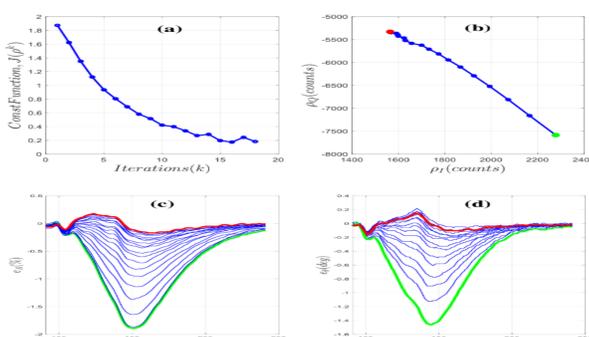


Figure 3. Low power test stand experiment: (a) Cost function; (b) Controller parameters; (c) Amplitude error for 150usec period covering beam loading transient; (d) Phase error for 150usec period covering beam loading transient; In the (b), (c), and (d), the green line (dot) show the initial values and red lines (dot) show the final values.

Iterative Feedforward Controller Tuning Application to Fine Tuning For LANSCE Proton Beam:

The proposed iterative feedforward controller tuning algorithm is applied for LANSCE 805-MHz Coupled Cavity Linacs (CCLs). Since the linac is producing an H⁻ proton beam for the users, before the proposed feedforward controller tuning algorithm is applied, the feedforward controller parameters are coarsely tuned by controller Phase Sweeping Method so that the amplitude error and the phase error are within the error requirements, $\pm 1.0\%$ amplitude error and $\pm 1.0^\circ$ phase error. The proposed tuning algorithm is then applied for fine tuning of the feedforward controller.

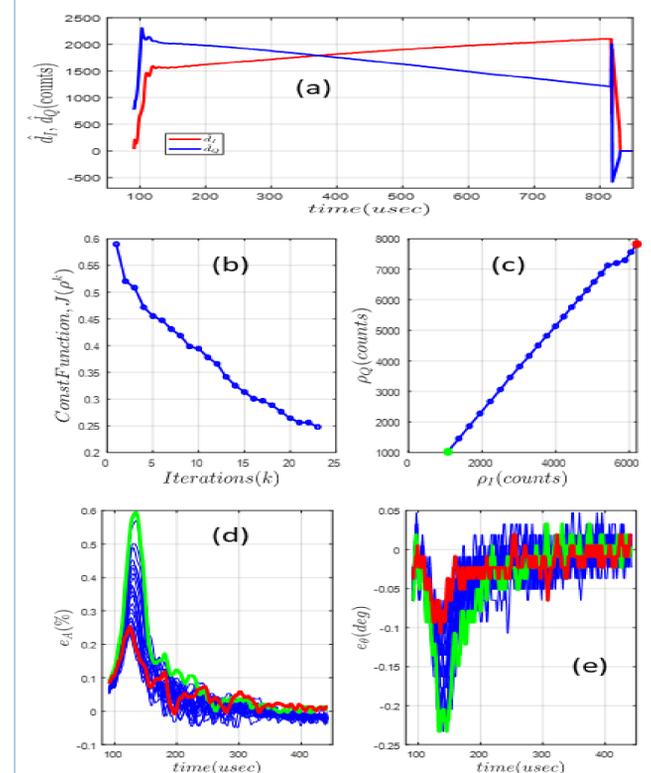


Figure 4. Performance results of the Iterative Tuning method for the Feedforward controller Fine Tune: Figure 3(a) shows the estimates \hat{d}_I, \hat{d}_Q of the I/Q components of the beam currents. Here, the 625-us-long beam is loaded at 90 us and DOB is enabled during the beam loading period. Figure 3(b) shows the cost function and Figure 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-us-long amplitude error e_A and phase error e_θ that cover the beam loading transient period.

Fine Tuning Results of CCL10, 16, and 17

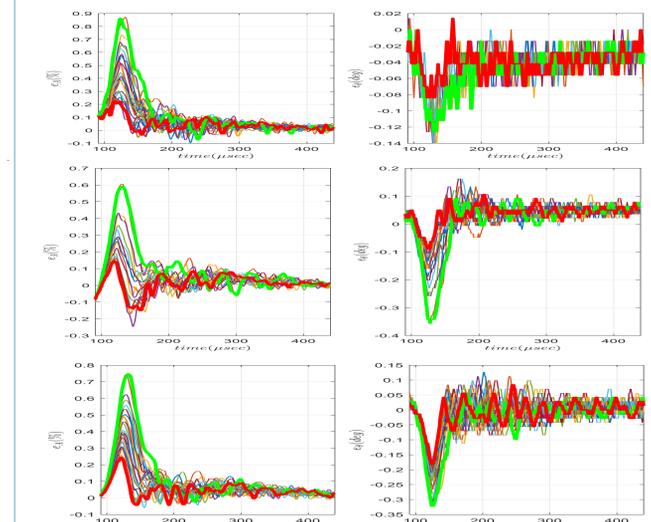


Figure 5. The Error Trajectories of 3 CCLs (top: CCL 10, middle: CCL 16, bottom: CCL 17). Left column shows Amplitude error trajectories and the right column shows phase error trajectories. Green line: trajectories at initial parameters; Red line: trajectories at the optimal parameters.

References

- [1] J. Lyles et al, "Installation and Operation of Replacement 201 MHz High Power RF System at LANSCE," IPAC 2015, Richmond, VA, USA.
- [2] Kwon, Sung-il, Lynch, Mike, and Prokop, Mark, "Decoupling PI controller for a normal conducting RF cavity using a recursive LEVENBERG-MARQUARDT algorithm," IEEE Trans. Nuclear Science.