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NORM-OPTIMAL ITERATIVE LEARNING CONTROL TO CANCEL BEAM LOADING EFFECT ON THE ACCELERATING FIELD

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Abstract

Iterative learning control (ILC) is an open loop control strategy that improves the performance of a repetitive system through learning from previous iterations. ILC can be used to compensate for a repetitive disturbance like the beam loading effect in resonators. In this work, we aim to use norm-optimal ILC to cancel beam loading effect. Norm-optimal ILC updates the control signal with the goal of minimizing a performance index, which results in monotonic convergence. Simulation results show that this controller improves beam loading compensation compared to a PI controller.

INTRODUCTION

In a linear accelerator, such as a cavity resonator, the goal is to establish and maintain a standing wave electromagnetic field with constant amplitude and phase. A feedback control loop is responsible for maintaining constant amplitude and phase despite various disturbances. The electromagnetic field within the cavity can be assumed as stored energy. When a bunch of particles passes through the cavity, a portion of the energy is transferred from the field to the beam, resulting in a drop in the accelerating field. This effect is referred to as beam loading.

Feedback controllers are not fast enough to compensate the beam loading effect. It is preferred to use feedforward controllers to preemptively counteract with the energy drop by increasing the cavity voltage just before the beam arrival. At Japan Proton Accelerator Research complex (J-PARC), a multi-harmonic RF feedforward system is used to compensate beam loading in 3 GeV rapid cycling synchrotron (RCS) [1]. The feedforward controller uses the wall current monitor (WCM) to pick up the beam signal I_{beam}. The controller then generates an additional signal equal to $-I_{beam}$ on top of the driving RF current. This control system compensates the beam loading of the three main harmonics ($h = 2, 4, 6$). In TESLA linear accelerator, adaptive feedforward control is used to compensate the beam loading and dynamic Lorentz force detuning [2].

In this work, we aim to use norm-optimal iterative learning control (NO-ILC) to cancel the beam loading effect. The idea of iterative learning control (ILC) is to improve the performance of a repetitive system through learning from previous iterations. NO-ILC is a model based iterative approach to optimally update the control signal and reduce the error monotonically. The control law is updated by minimizing a performance index which penalizes the error and the difference between the control signal in two consecutive iterations. NO-ILC has been used on Free Electron Laser at DESY [3]. It guarantees that the error decreases monotonically [4], and we can change the rate of convergence by tuning parameters.

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PROBLEM FORMULATION

The dynamical behavior of a cavity resonator is well known in accelerator physics and can be described by [5]

$$\frac{d}{dt}\begin{bmatrix}V_I(t)\\V_Q(t)\end{bmatrix} = \begin{bmatrix}-\omega_h & -\Delta\omega\\ \Delta\omega & -\omega_h\end{bmatrix}\begin{bmatrix}V_I(t)\\V_Q(t)\end{bmatrix} + \begin{bmatrix}\omega_h & 0\\ 0 & \omega_h\end{bmatrix}\begin{bmatrix}u_I(t)\\u_Q(t)\end{bmatrix}, \quad (1)$$

where V_I and V_Q are the real and imaginary parts of the complex cavity voltage V, ω_h is the half bandwidth of the cavity, $\Delta\omega$ is the detuning, and u_I and u_Q are the real and imaginary parts of the complex driving voltage.

The cavity resonator dynamics can be reformulated as a state space system as

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t)\\ y &= Cx(t),\end{aligned} \quad (2)$$

where the states, input and output are respectively given by $x(t) = \begin{bmatrix}V_I(t)\\V_Q(t)\end{bmatrix}$, $u(t) = \begin{bmatrix}u_I(t)\\u_Q(t)\end{bmatrix}$ and $y(t) = \begin{bmatrix}V_I(t)\\V_Q(t)\end{bmatrix}$,

and the state space matrices are introduced as follows

$$\begin{aligned}A &= \begin{bmatrix}-\omega_h & -\Delta\omega\\ \Delta\omega & -\omega_h\end{bmatrix}\\ B &= \begin{bmatrix}\omega_h & 0\\ 0 & \omega_h\end{bmatrix}\\ C &= \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\end{aligned} \quad (3)$$

The transfer functions from the inputs to the outputs can be found using $G(s) = C(sI - A)^{-1}B$ as

$$\begin{bmatrix}V_I(s)\\V_Q(s)\end{bmatrix} = \frac{1}{D(s)}\begin{bmatrix}\frac{s}{\omega_h}+1 & -\frac{\Delta\omega}{\omega_h}\\ \frac{\Delta\omega}{\omega_h} & \frac{s}{\omega_h}+1\end{bmatrix}\begin{bmatrix}u_I(t)\\u_Q(t)\end{bmatrix}, \quad (4)$$

with $D(s) = (\frac{s}{\omega_h}+1)^2+(\frac{\Delta\omega}{\omega_h})^2$. This cavity model is valid around the baseband frequency, for a single fundamental mode (π-mode). This model will be used to develop the NO-ILC.

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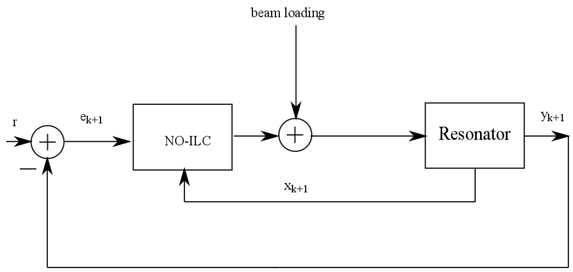

Figure 1: Block diagram of norm-optimal ILC.

Since NO-ILC includes both feedback and feedforward mechanisms, it replaces the PI controller in the loop. A block diagram of the control loop with NO-ILC is shown in Figure 1.

The goal of the NO-ILC is to generate a control signal at the $k+1$ iteration u_{k+1} to minimize the performance index given by

$$J_{k+1}(u_k+1) = \|e_{k+1}\|^2 + \|u_{k+1} - u_k\|^2, \tag{5}$$

where $e_{k+1} = r - y_{k+1}$ and r is the desired trajectory of the output, and $\|.\|$ represents the appropriate norms. In optimal control, the norms are usually represented as quadratic forms

$$\begin{aligned} \|e_{k+1}\|^2 &= e_{k+1}^T Q(t) e_{k+1} \\ \|u_{k+1} - u_k\|^2 &= (u_{k+1} - u_k)^T R(t)(u_{k+1} - u_k) \end{aligned} \tag{6}$$

where $Q(t)$ and $R(t)$ are symmetric positive definite weight matrices, which can be used as tuning parameters.

NO-ILC uses the error and state information from current and previous trials to update the control signal and minimize the performance index. This controller is implemented in three steps [4].

In the first step, which is done offline, we find the matrix gain $K(t)$ as the solution of the discrete matrix Riccati equation. This equation is solved backward on the time interval $t \in [0, N-1]$ where we have the terminal condition $K(N) = 0$, and solve backward to find the previous gain matrices. The Riccati equation is given by

$$\begin{aligned} &K(t) = A^T K(t+1)A + C^T Q(t+1)C - \\ &A^T K(t+1)B(B^T K(t+1)B + R(t+1))^{-1} B^T K(t+1)A \end{aligned} \tag{7}$$

The second step, which is performed between the trials, is calculating the feedforward term $\zeta_{k+1}(t)$. Again, we have the terminal condition $\zeta_{k+1}(N) = 0$, and solve backward to find the previous predictive terms. The feedforward term is calculated using the matrix gain $K(t)$ which was calculated in the previous step, and the error information from the previous trial as follows

Table 1: Simulation Parameters

Q_L	3840
f_0	342 MHz
T_s	1 μs
N	1000
ω_h	279800 rad/sec
$\Delta\omega$	0.0628 rad/sec
K_p	0.04
K_i	0.3
Q	2
R	5

$$\begin{aligned} \zeta_{k+1}(t) = &(I + K(t)BR^{-1}(t)B^T)^{-1} \\ &(A^T \zeta_{k+1}(t+1) + C^T Q(t) e_k(t)) \end{aligned} \tag{8}$$

Finally the third step, which is executed at each sampling instant, updates the control signal as

$$\begin{aligned} &u_{k+1}(t) = u_k(t) - \\ &(B^T K(t)B + R(t))^{-1} B^T K(t) A[x_{k+1}(t) - x_k(t)] + \\ &R^{-1}(t) B^T \zeta_{k+1}(t). \end{aligned} \tag{9}$$

The updating law includes both a feedback and a feedforward component.

SIMULATION RESULTS

The block diagram in Figure 1 was simulated in Matlab. The cavity was simulated as a multi-input multi-output (MIMO) system. The simulation parameters are shown in the Table 1.

In the table, Q_L is the loaded quality factor, f_0 is the resonance frequency, T_s is the sampling time, N is the number of samples per iterations, ω_h is the bandwidth of the cavity, $\Delta\omega$ is the detuning, K_p and K_i are the proportional and integral gain of the PI controller respectively, and Q and R are used to form the weighting matrices, which are assumed to be time-independent.

Each iteration is assumed to last for 1 millisecond. The RF pulse starts at $N = 200$ and ends at $N = 800$. The beam loading, which is assumed to be a step disturbance at the input of the cavity, starts at $N = 400$ and ends at $N = 600$.

The simulation is run once with only PI controller in the loop, and once with NO-ILC. The performance of the system in these two cases is compared in Figures 2 and 3.

Figure 2 shows the overall performance of the system during one pulse, and Figure 3 is zoomed in to emphasize and clearly show beam loading compensation after 30 iterations. The simulation results show that NO-ILC can successfully reject beam loading disturbance and the performance is more satisfactory compared to the PI controller.

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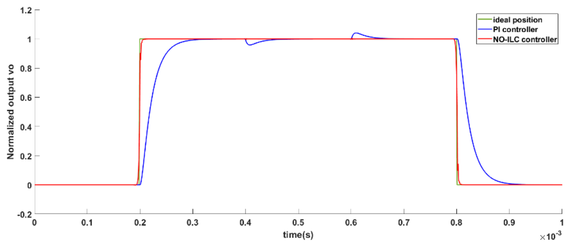

Figure 2: Comparison of system performance for PI and NI-ILC after 30 iterations.

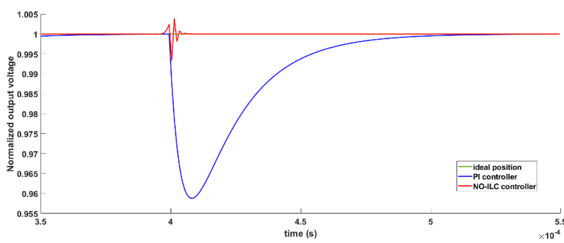

Figure 3: Comparison of beam loading compensation for PI and NO-ILC after 30 iterations.

CONCLUSIONS

Beam loading effect is a repetitive disturbance and a feed forward controller can be used to deal with it faster than a feedback loop. Iterative learning control is an open loop control strategy that uses the error information from the previous iteration to improve the control output at the current iteration. In this work, we used NO-ILC to replace both feedback and feedforward loops, monotonically decrease the error and compensate for the beam loading disturbance within 30 iterations.

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