A PROTOTYPE FAST FEEDBACK SYSYEM FOR ENERGY LOCK AT CEBAF*

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The beam energy of CEBAF must be controlled accurately against phase and gradient fluctuations in RF cavities in order to achieve a 2.5 x 10^{-5} relative energy spread. A prototype fast feedback system based on the concepts of Modern Control Theory has been implemented in the CEBAF Control System to function as an energy lock. Measurements performed during the pulsed mode operations indicate presence of noise components at 4 Hz and 12 Hz on beam energy. This fast feedback prototype operates at 60 Hz rate and is integrated with EPICS. This paper describes the implementation of the fast feedback prototype, and operational experience with this system at CEBAF.

I. INTRODUCTION

The CEBAF accelerator consists of 45 MeV injector, two side-by-side superconducting linacs, and 9 recirculation arcs that recirculate the beam through the linacs up to 5 times for 4 GeV total energy. The energy spread in the emerging beam is determined by the bunch length, which is tightly controlled at CEBAF, and by the stability of the amplitude and phase of the RF fields in the superconducting cavities. The design specification for energy spread is $\sigma_E/E = 2.5\times10^{-5}$. A measurement of beam position in a high dispersion region of the arc can determine the relative energy of the beam to this precision. Then, the measured energy can be stabilized by changing the RF control settings in a feedback loop.

A prototype system has been built to test the techniques and ideas that will ultimately be used to develop an accelerator-wide generic fast feedback facility based on concepts of modern control theory. The energy and orbit lock applications are the first applications in this development.

II. DESIGN CONCEPTS

The primary objective for this feedback loop is to eliminate variations in the beam energy in the injector region up to 10 Hz rate. The measurement of beam energy fluctuations is obtained from Beam Position Monitors (BPMs) located in high dispersion region in the injection chicane. The correction required in the beam energy is achieved by modulating the accelerating gradient in selected corrector cavities upstream of the BPMs. The control input signal for modulating the accelerating gradient is calculated using the BPM measurements of current sample instant and the state of the system at previous sample instant. The controller design is based on Linear Quadratic Gaussian [1] controller/estimator design. The optimal controller is designed based on system dynamics model, process and measurement noise statistics.

III. CONTROLLER/ESTIMATOR DESIGN

The description of the system in state space formalism is given by

$$x(k+1) = \Phi x(k) + \Gamma u(k) + w(k) \qquad EQ\ 1$$

$$y(k) = Hx(k) + v(k) \qquad EQ\ 2$$

x(k) is the state vector which contains the attributes of the system that are dynamically significant, Φ is the system dynamic matrix which takes system from state k to state $k+1$, Γ is the control input matrix which takes the control inputs to the state vector, *u(k)* is the vector of control inputs to the system, *w(k)* is the process noise vector. *y(k)* is vector of measurements, *H* is the measurement matrix which takes the measurements to states, *v(k)* is the measurement noise vector

For this energy lock system, the state vector is $x = [X_o, X'_o, Y_o, Y_o', \Delta E/E]$ which contains the beam position and angle in X and Y directions and $\Delta E/E$ is the energy variation at a reference point coming into the chicane. The *H* matrix contains the transfer matrix terms R_{11}, R_{12}, R_{33}, R_{34} for the BPMs from a reference point.

A Kalman filter is used to estimate the states from the BPM measurements. The measurement update from sample instant k is obtained using

$$\hat{x}(k) = \bar{x}(k) + L(y(k) - H\bar{x}(k)) \qquad EQ\ 3$$

and the time update that takes the state vector from sample instant k to $k+1$ using

$$\bar{x}(k+1) = \Phi\hat{x}(k) + \Gamma u(k) \qquad EQ\ 4$$

Here $\hat{x}(k)$ is the estimated state vector and $\bar{x}(k+1)$ is the predicted state vector for sample instant $k+1$ obtained from the estimated state at time instant k. The controller equations that are used for the feedback loop can be obtained by combining the above two equations and are described as

$$\bar{x}(k+1) = \Phi\bar{x}(k) + \Gamma u(k) + \Phi L(y(k) - H\bar{x}(k)) \qquad EQ\ 5$$

$$\hat{y}(k) = (H - HLH)\bar{x}(k) + HLy(k) \qquad EQ\ 6$$

$$u(k) = -K\cdot\hat{x}(k) \qquad EQ\ 7$$

L is the state estimator gain matrix and *K* is the output gain

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matrix. The equation 5 is used to estimate the state vector at next sample instant *k+1*. This equation contains three terms. The first term uses the system dynamic matrix Φ and the state vector at time *k* and calculates new state. The second term which uses the control input matrix Γ puts in the effect of actuator settings on the state. The third term is the correction term between estimated and actual states obtained from the measurements. Equation 7 is used to calculate the actuator setting based on current state estimate using negative state feedback through an optimal gain matrix *K*.

K and *L* matrices are computed off-line using Matlab [5] from the solution to an algebraic Riccati Equation [1]. This equation is obtained from minimization of a functional for the chosen performance criteria for this system. Satisfactory response of controller and estimator is verified by performing simulations of the closed loop system using Simulink [5]. If the response controller and estimator for system performance specification is found satisfactory, the calculated matrices are stored in a file which is read at the time of feedback loop initialization.

IV. IMPLEMENTATION

The control hardware for the energy lock BPMs and the corrector cavities is located in 2 separate buildings, Fig 1, and is therefore controlled by two different I/O controllers (IOC-Motorola 68040) which are linked by Ethernet.

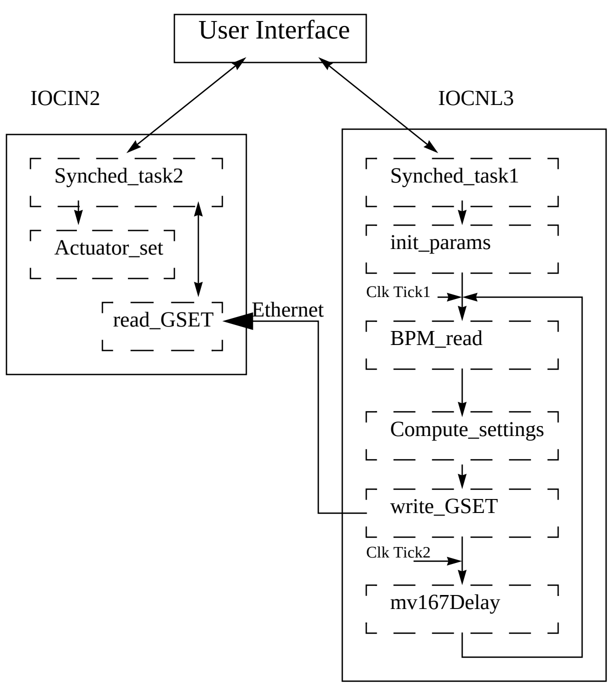

Fig 1

The energy variations are measured using 4 BPMs in the Injection Chicane. BPM data is obtained from the B0007 board (specialized data acquisition module for BPMs) resident in a CAMAC crate on a serial highway loop that is controlled by a diagnostics IOC (IOCNL3).The accelerating gradient set-point on two corrector cavities is modulated in order to correct for energy fluctuations. The computed corrective signals are sent through a DAC as a ± 5 V signal to the analog offset inputs on RF control module. The DAC card is resident in a CAMAC crate close to the RF control module. This CAMAC crate is on a serial highway loop controlled by an RF IOC (which is IOCIN2). The communication between these two IOCs is done over Ethernet.

The feedback loop software is divided in two parts: EPICS [2] software and VxWorks [3] software. EPICS software manages the Graphical User Interface (GUI) for the feedback loop, triggers the appropriate modules of VxWorks software as required, and monitors the status of the loop.The organization of the VxWorks software is described using Fig 1. The *Synched_task1* and *Synched_task2* routines synchronously execute the various modules on two IOCs as shown in Fig 1. These routines are triggered ON/OFF when the user turns the energy lock loop ON/OFF. During the pulsed mode operation, the synchronization for sampling and correction for the feedback loop is done using the beam synchronization pulse signal.

Upon start-up, the *init_params* routine initializes the various parameters and matrices used by the feedback loop such as the controller gain matrix *K*, the estimator gain matrix *L*, the transfer matrix *H* for 4 BPMs, the BPM hardware constants and previously saved reference orbit settings. After initialization, the *Synched_task1* routine polls for the LAM signal; once the LAM has been received and reset, the *BPM_read* module is called. In order to obtain the BPM measurements at 60 Hz rate the B0007 hardware is accessed directly rather than obtaining these signals from the accelerator control system. The *BPM_read* module performs CAMAC reads to obtain the beam position data in X and Y planes from the B0007 card for individual BPMs. The beam position is calculated from the wire signals using calculations described in Ref. [4]. Then, *Compute_settings* uses the energy variation measurements obtained from the BPM data and computes the correction signal using equations described in previous section. The correction signal is sent to the IOCIN2 over Ethernet. A client/server set-up of TCP/IP protocol is used for data transfer over Ethernet. Communication between two IOCs through client and server stream sockets is set up at the time of IOC initialization.

In every cycle of the measurement, computation of settings and actuation, two time measurements, Fig 1, are done using the auxiliary system clock on the IOC. From these two time measurements, the amount of time S*ynched_task1* has to sleep before next sampling instant is computed and *mv167Delay* routine is used to effect it.

Synched_task2 on the IOCIN2 calls *read_GSET* to obtain the gradient setpoint correction signal. Once this data has been received, *Actuator_set* is called to send the gradient setpoint signal to the vernier cavities. *Actuator_set* performs CAMAC writes to the DAC card to effect the correction signal.

V. RESULTS

One of requirements on the state estimator for this system is that the estimator should be able to distinguish between position changes caused by energy variations and that caused by betatron oscillations. Since there is no coupling in the X and Y planes a change in X position should not affect the Y position at the reference point. A series of open loop tests were performed to study the estimator response to position and energy changes. The results of these tests indicate a satisfactory response of state estimator. For the first part, a change in energy of 0.2 MeV was introduced by changing the accelerating gradient in two cavities upstream of energy lock location. The state estimator converged within 2-3 samples to the actual energy error introduced while X, X’, Y, Y’ were not affected.

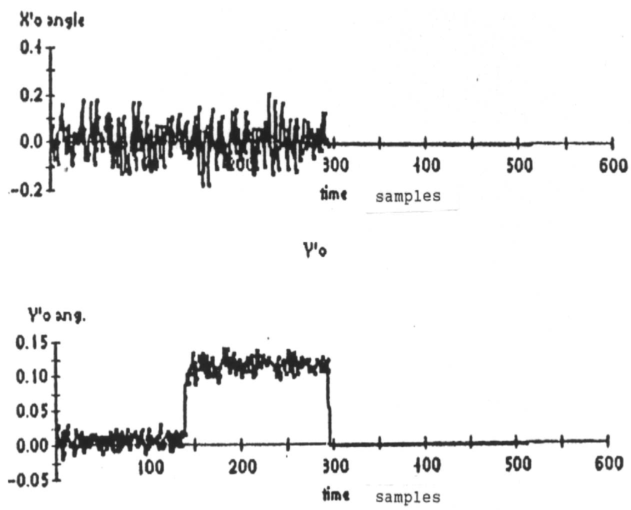

Fig 2

Next, a vertical corrector near the reference point was changed by 15 G.cm to introduce an angular change of 0.1 mrad in the Y’ estimate. The estimator learned (Fig 2) of this change within 2-3 samples without affecting other states. A similar test for X’ state was done using a horizontal corrector and similar results were observed. Initial tests of closed loop system response indicate that the energy lock loop is functional and it is able to lock the energy of beam against step changes in the energy introduced by changing the accelerating gradients of the cavities upstream of energy lock location. Fig 3a shows the $\Delta E/E$ after the step change in the energy was introduced and before the loop was closed. Fig 3b shows the $\Delta E/E$ after the loop was closed. Due to machine commissioning constraints we have had minimal closed loop testing time. More beam time is needed in order to collect data for producing a Bode plot of closed loop system response.

Ethernet has been used for transfer of correction signal between two IOCs at 60 Hz rate. Initial data obtained indicates that Ethernet can be successfully be used to run the feedback loop at higher rate of 240 Hz reliably.

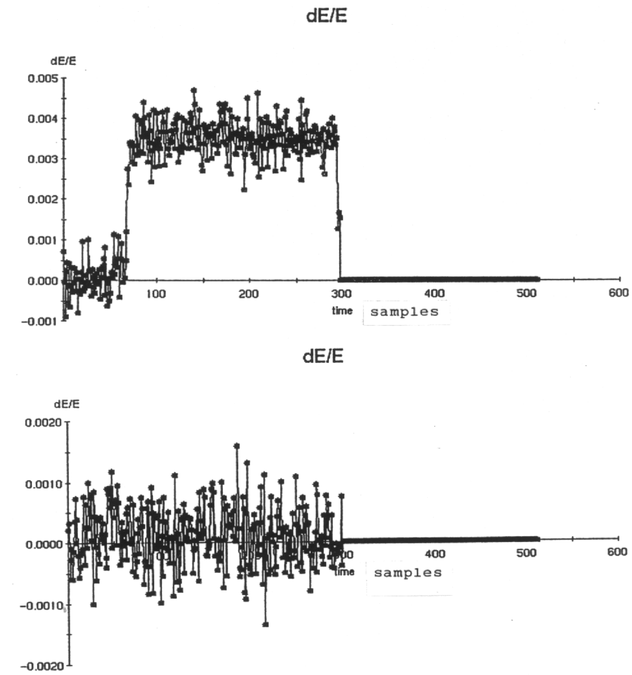

Fig 3

VI. CONCLUSIONS

Implementation of this feedback loop indicates that control design techniques based on concepts of Modern Control Theory can be successfully used for applications at CEBAF. A fast orbit lock controller designed using these techniques will be implemented in the Injector region at CEBAF shortly. Experience gained from implementation of these two loops will be used in developing a generic fast feedback facility for CEBAF.

VI. REFERENCES

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