PROGRAM FOR AUTOMATIC CONTROL OF BEAM TRANSFER LINES

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The traditional manual tuning of the beam transfer lines becomes inefficient with the increasing of both the beamlines length and the number of the magnets.That's why computer controlled beamlines are widely used now [1-3] .The set of programs is presented,which can be used for beamline automatic control.

1.Mathematical Formulation of the Problem

Let A_i be the transfer matrix between the monitors M_i and M_{i+1} and B_i be the influence of the correctors on the beam,which are located between these monitors.If X_i is the beam state vector on the i monitor,which is consisted of r and z coordinates and of their derivatives,then one will have

$$X_{i+1}=A_iX_i+B_iU_i, \quad i=0,1,\dots,n, \qquad (1)$$

where U_i is the vector which includes the strength of the correctors and n is the number of the monitors.

Usually we get the coordinates r and z with some errors from the monitors.The observation vector on the i monitor will be

$$Z_i=H_iX_i+V_i, \quad i=0,1,\dots,n, \qquad (2)$$

where H_i is the matrix for separation of the coordinates from the state vector,V_i is the measurement errors.

Let's discuss some versions of the mathematical formulation of the beamline optimal control versus the sequence of observation and control.

1. It is assumed that after sequential measurements of beam coordinates Z_i , $i=0,1,\dots n$ we need to calculate the control vector U_k.If to take the result of minimizing

$$J=1/2||X_n||^2_S + 1/2\sum_{k=0}^{n-1}(||X_k||^2_Q + ||U_k||^2_R) \qquad (3)$$

with the constraints (1),(2) as a criterion of optimal U_k,we shall have a well known problem of optimal regulator [4], where S,Q and R are weighting matrices. Here

$||U_k||^2_S = U_k^T R U_k$. Optimal control will be

$$U_k=-L_k\bar{X}_k, \qquad (4)$$

where the matrix L_k is a result of Ricatti equation solved backward in time

$$L_k=R^{-1}B_k^T(P_{k+1}^{-1}+B_kR^{-1}B_k^T)^{-1}A_k, \qquad (5)$$

$$P_k=Q+A_k^T(P_{k+1}^{-1}+B_kR^{-1}B_k^T)A_k, \qquad (6)$$

where $P_n=S$ and k is changed from n-1 to 0. X_k is the estimate of the state vector formed by the Kalman filter [4]

$$\bar{X}_k^{j+1}=\bar{X}_k^j+\bar{P}_{j+1}^j A_j^T H_{j+1}^T R^{-1}(Z_{j+1}-H_{j+1}A_jX_k-\bar{H}_{j+1}^j B_jU_j),$$

$$P_{j+1}=P_j-P_jA_j^TH_{j+1}^T(H_{j+1}A_jP_jA_j^TH_{j+1}^T+R)^{-1}H_{j+1}A_jP_j,$$

where $\bar{X}_k^0$ is the initial guess of X_k state vector and if more information is available it can be the mean value of X_k, R is the noise covariance matrix of $\bar{X}_k$, it shows the uncertainty of the initial guess and during the iteration procedure its diagonal components are decreasing, because the increase of available information reduces the parameter uncertainty.In this algorithm if the aprior information is not sufficient to get the Kalman estimation i.e. the matrices P_0,R and the mean value of X_k are not known, then one can use the sequential least square estimation or optimal estimation of maximal likelihood estimator ($\bar{X}_k^0=0$ and $P_0\to\infty$). It is important that the calculations structure is the same for all cases. These algorithms are attractive, because they are efficient in the case that there are unknown parameters in matrix A_j.

2.From the measurements of Z_i on the all monitors one can estimate state vector X_0 and after that calculate the optimal control U_i.

The estimation of $\bar{X}_0$ one can do with the Kalman filter and the control U_k can be

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calculated by the (4), where the sequence of

$$X_{i+1}=A_iX_i+B_iU_i, \qquad \bar{X}_0=X_0 \tag{7}$$

can be used as X_k.

3. It is easy to get

$$X=AX_0+BU, \tag{8}$$

$$HX=HAX_0+HBU \tag{9}$$

from (1), (2), where

$$X=[X_1,X_2,\ldots,X_n]^T,$$

$$U=[U_1,U_2,\ldots,U_n]^T,$$

$$Z=[Z_1,Z_2,\ldots,Z_n]^T,$$

$$H=[H_1,H_2,\ldots,H_n]^T,$$

$$V=[V_1,V_2,\ldots,V_n]^T.$$

The aim of optimal control is to have $||HX||^2 \rightarrow 0$. If $||HX|| \cong 0$, then

$$HAX_0=-HBU, \qquad Z=HAX_0+V,$$

$$Z=-HBU+V \tag{10}$$

If we consider (10) as linear model of observation of Z_i measurements, the optimal estimation of U can be realized with the sequential Kalman estimator.

We consider, that the least approach of optimal control formation must be most efficient practically in spite of its heuristical form, because it is simple in calculation and the aprior information about B matrix can be easily improved experimentally by the simple calculation.

2. The Structure of the Program

A set of programs is written for the investigation of the estimation and control algorithms. The programs consist of several modules, each of them can be operated separately in real time scale.

The "TRANSPORT" [5] formalism is used here. The structure of the beamline is the input file of the program. It can include bending magnets, quadrupoles, synchroytron magnets, correctors. The tilts of the elements are given by the rotation matrix. The corrector is assumed to be an element which gives a kick in the middle.

It is possible to simulate the disturbances of the elements by vertical and horizontal kicks in the middle of each element. The program consists of following modules:

- the module of beam trajectory simulation;
- estimation of the beam parameters $X, X', Z, Z', \Delta P/P$;
- the control module.

This modules can operate separately using the structure file of the beamline. The control module is consisted subroutines of optimization based on the least square method (ordinary and sequential) and the subroutines for making local corrections.

3. The Results of Simulations

The efficiency of the algorithms are investigated on the electron beam transfer line from PETRA to HERA. The beam line is about 219 meter and is consisted of 19 bending magnets and 19 quadrupoles. The control system includes 20 monitors and 22 correctors: 12 vertical and 10 horizontal. Almost all the monitors and the correctors are attached to the quadrupoles. The tiltes of bending magnets and the quadrupoles cause the coupling of horizontal and vertical motion [6].

The process of measurement from the monitor is simulated with help of the beam trajectory simulation module and random number generation program. The normal distributed noise with 0 mean value and variance of 1mm is used (the accuracy of the monitors is of 0.5mm).

The beam initial parameters estimation quality and efficiency of control algorithms are investigated.

1. The beam parameters estimation.

The sequential maximal likelihood filter is used. The general results of the simulation are:

- the estimation convergence is not sensitive to the initial elements of covariance matrix P_0 if their are chosen to be 10^5 10^6 order of magnitude of the X_0 and the initial values of X_0 are 0;
- after 10 iterations estimated values are in the range of tolerable accuracy.

The typical process of parameters

X=2mm, X =0.1mrad, Z=1mm, Z =0.1mrad, $\Delta P/P$=0.2% estimation versus the number of iteration are in fig.1-5.

2.The optimal control estimation.

The distorted trajectory is the result of not 0 initial X_0 values and/or disturbances of the beamline elements.The estimation is done by the algorithm 3 without X_0 estimation using sequential least square algorithm (maximal likelihood).

The results of the simulation show that after 5 iteration the corrected trajectory is in the range of tolerable accuracy.

The typical results of the control algorithm are shown in fig.6,7.Here the trajectories before and after correction are presented.

References

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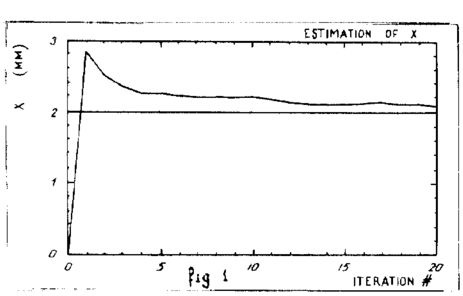

Fig 1

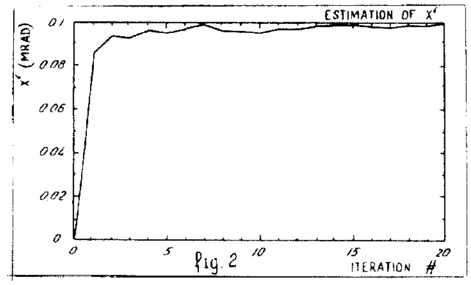

Fig. 2

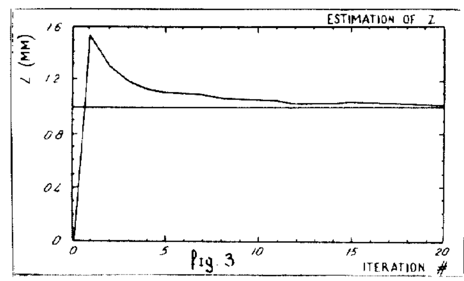

Fig. 3

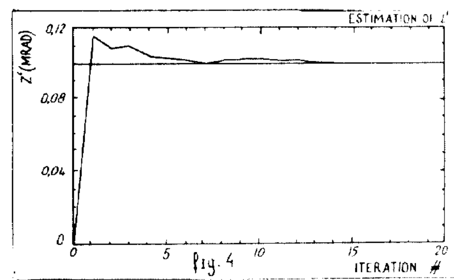

Fig. 4

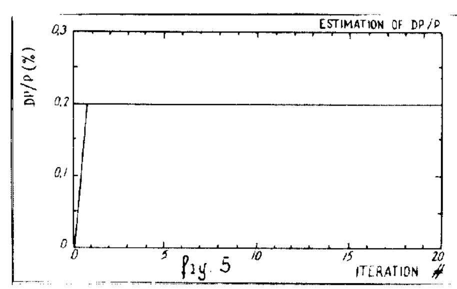

Fig. 5

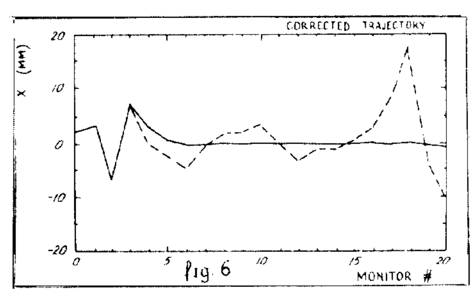

Fig. 6

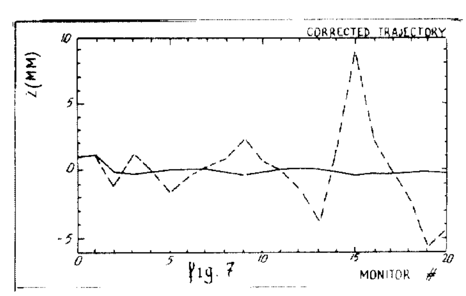

Fig. 7