Experimental Investigation of Optimization Control Methods in a Proton Synchrotron

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Abstract

The paper is devoted to development of adaptive methods of optimal control, which make it possible to attain in an automatic mode the maximum intensity of the accelerated particle beam for particular operation conditions and to track it continuously during operation of an accelerator. The investigation results are discussed.

1 Introduction

The method of attack involves both the identification of a control object and the use of a model in the control loop, as well as the application of seek optimization methods.

Most physical processes proceeding in accelerators have a well-defined mathematical interpretation, which constitutes a system of differential equations. At the same time, the physical processes themselves described by each of the equation groups are closely related. The use of such models encounters the following difficulties:

- implicit form of the equations regarding the control actions and the complexity of their solution in the analytical and digital form in real time;
- a model does not take into account the specific character of a real object, its structural and technological features;
- a model does not consider possible changes in environmental conditions, inaccuracies in measurement, etc.

The lack of definiteness suggests that adaptable models be considered, that have the degree of freedom in the form of parameters whose values may be refined on the basis of a posterior information. Practically this principle can be realized by controlling separate accelerator systems with a small dimensionality of the control space and a relatively simple dependence between the output parameters and controls [1].

Noise, which can cause a continuous drift of output parameters, has a profound effect on the optimization of the control process. It can be difficult to get a true measure of the desired information channel from a set of points into which a number of different sources are injecting noise.

From the information point of view, indetermination and randomness are the characteristic features of an accelerator, and it is statistical methods which must be used to investigate and identify such features. Thus, the law is replaced with an empirical model based on experimental data, which takes into account particular essential features and properties of the facility.

2 Experimental and statistical investigations

The 10 GeV proton synchrotron (Moscow) was used as an investigation object. On the basis of a priori information the following independent variables were taken as the factor vector: x_1-voltage on an electrostatic inflector; x_2-current of the last ion guide magnet; x_3-current of the last vertical corrector; x_4-current of the last-but-one vertical corrector; $x_{5\text{-}9}$-currents of orbit corrections Sin13R, Cos13R, Sin13Z, Cos13Z, Cos14R; x_{10}-field intensity at injection moment; x_{11} - radio frequency correction.

The statistical intensity properties, i.e. dispersion, reproducibility, stationary state, distribution law, were estimated on the basis of a passive experiment. Intensity dispersion was found to vary considerably with time and to be dependent on the level of the intensity itself, so we have every reason to reject the hypothesis of sampling distribution normality. The analysis of active experiment results aims at:

- determining the character of the dependence between each factor and accelerated beam intensity;
- determining the geometrical properties of the response surface.

Variations of the factors in the active experiment were done via the simplex technique [2].

The analysis results demonstrated that most coefficients of pair correlation, according to Student′s criterion [3], are in general essential but in this case small. Consequently, a fraction of the linear dependence between Y and X is small. The obtained estimate prevents accepting the hypothesis on the existence of only a linear dependence contribution to the general dependence between Y and the factor vector.

To determine the nonlinear dependence contribution the use was made of Pearson correlation ratio [3]. The estimates of the correlation ratios proved to be comparatively large (0.15 – 0.2), this favoring the nonlinear dependence. But, they are far from unity, forcing us to admit the effect of uncontrollable factors as being considerable.

Some geometrical properties of the response surface were investigated by constructing a set of axial sections. The analysis revealed that all axial sections constitute one-extreme convex curves. Nonseparability of the object resulting, for example, from interaction between radio frequency and injection field level, should be considered as a characteristic feature. As a result, a ″ridge″ situation occurs on the response function surface. One more feature manifests itself in the existence of a plateau in the extremum zone for most control variables, testifying to the possibility to reach a steady-state mode.

It was found also that the extremum drifted in level and in the factor space and that the gradient of partial sections varied with time.

The model in the form of a square polynomial was accepted for the analytical expression of the response func-

tion: $Y=B_0+X^T BX+X^T B_1$

The total number of unknown parameters of the polynomial is 78. The least-squares method was used to calculate the coefficients. With the transformation $q=y^{0.5}$, there are no reasons to reject the hypothesis that the output parameters are normally distributed.

The simplex technique of the second order was accepted as an experiment design matrix. The experiment consisted of 80 runs. Regression coefficients were estimated on the basis of experiment data. The estimation of dispersion made by Fischer criterion[3] does not reject the hypothesis of the adequacy of the experimental data to the accepted polynomial. To classify the response surface the regression equation was brought to the canonical form:

$$q - q_0 = \sum_{i=1}^{11} (Z'_i - Z_{0i})^2 B_i$$

where Z_{0i} - coordinates of the symmetry center in the initial coordinate system, q_0 - response in the symmetry center. The determination of the coefficients B_i revealed that the obtained model is an 11-dimensional hyperbolic paraboloid.

The investigation results force us to recognize the entropy of an output variable caused by uncontrollable factors as being rather high and point to serious difficulties associated with the use of analytical and regression models for purposes of an optimal control over large cyclic accelerators.

3 Synthesis and realization of extreme control algorithms

When setting the problem of a priori selection of seek methods, apart from the results of the analysis of an accelerator used as a control object, account must be taken of the requirements for the control system itself, i.e. speed of operation, low introduced dispersion of the output parameter, noise stability, ability to orient itself in complicated situations, reliability. These requirements minimized the number of competitive methods. These are the simplex method and the random seek in modifications for optimization problem solution and the Gauss-Seidel method, apart from the above, for the extreme regulation.

The theory of these methods does not make it possible to define the domain and differentiated conditions of their application. Hence, the necessity arises for experimental investigations, though their results are specific and can be used to solve particular problems. The investigations of the seek methods on the models simulating the general situation in accelerators aimed at obtaining comparative characteristics of the methods in the extreme control mode.

The investigated seek methods are briefly described and their comparative characteristics are given in Ref.[4]. The simplex method, the random seeking by the best sample (RSBS) and the methods of stochastic gradient and stochastic approximation proved to be the most acceptable for the extreme control.

The main problem of the algorithm synthesis is to provide its workability under drift and noises. The level of noises can be as high as 20–30%. Hence, the necessity arises for statistical filtration of noises to provide the workability of the seek methods, in particular, to exclude anomalous measurements.

Success or failure of the next seeking step can be predicted, providing the quality function is plausible. Preference was given during its determination to the method of stable estimation, i.e. the estimation of the sampling median. The working algorithm envisages adaptation of the sampling volume to a value of the noise level.

Indetermination in attaining the extremum moment made it necessary to formulate the shut-down rule, which was taken by the number of unsuccessful steps in succession. To exclude premature, for different reasons, step degeneration, provision is made for relaxation, i.e. the start is repeated from the best attained point. The problem of global search is solved in the same way.

The methods demonstrating the best results during simulations were used as the basis for the extreme control algorithms for investigations on an accelerator.

The investigations were performed on the proton accelerator at the Institute of Theoretical and Experimental Physics (Moscow). To obtain reliable results, when comparing the efficiency of the methods, the ascension was repeated many times under different conditions naturally and artificially produced. Speed, seek dispersion and reliability were investigated.

The investigation of the optimization algorithm by the simplex method revealed that an observable increase in the intensity was terminated in 60–80 steps. The extremum is attained after two relaxation′s. Fig.1 presents the optimization process recorded by this method immediately after six-hour shut-down of the accelerator during preventive maintenance. As a result, the levels of all controls changed, the intensity increased by 120%. Dispersion in the extremum zone turned out to be much less than at the start.

The system detuning situation was reproduced for all controls. The extremum was known. Optimization was terminated after two relaxation′s (Fig.2). Average intensity values in the initial point and after optimization were

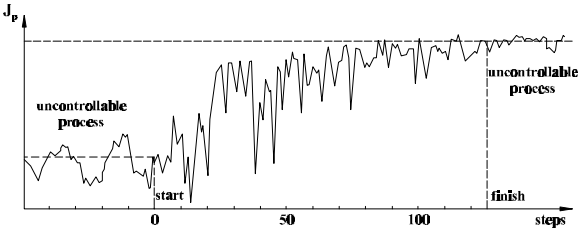

Fig.1 The process of optimization by the simplex method after preventive maintenance.

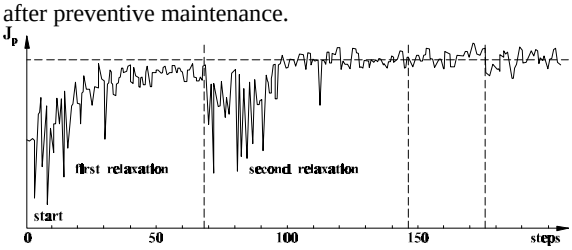

Fig.2 The process of optimization by the simplex method after system detuning through all 11 control parameters.

nearly the same.

Adjustment of the accelerator using the relaxation′s is shown in Fig.3. The accelerator was detuned through all 11 controls and the optimization system was started up by the RSBS method. After two relaxation′s the intensity level

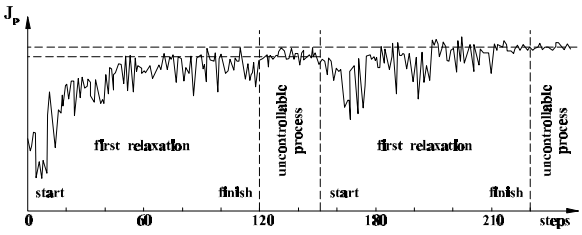

Fig.3. The process of optimization RSBS method in mode with relaxation′s

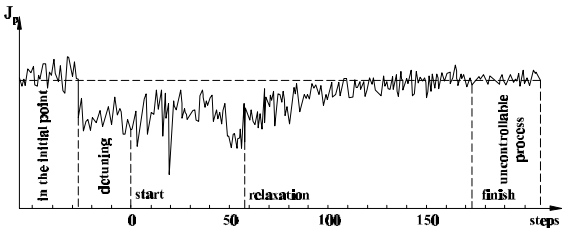

Fig.4. The process of optimization by the RSBS method with the start from an artificial ″ridge″″.

was completely recovered. The RSBS method demonstrated good results in the ″ridge″ situation, which was simulated by detuning radio frequency (Fig.4). The intensity level completely recovered. Intensity dispersion was markedly decreased as compared with dispersion in the initial point.

Fig.5 presents the application of the simplex method in the extreme regulation mode. The start was made from a

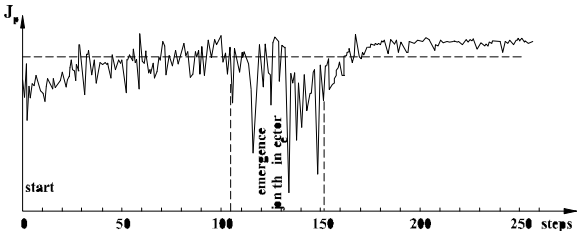

Fig.5. The process of extremum tracking by the RSBS method (fast drift).

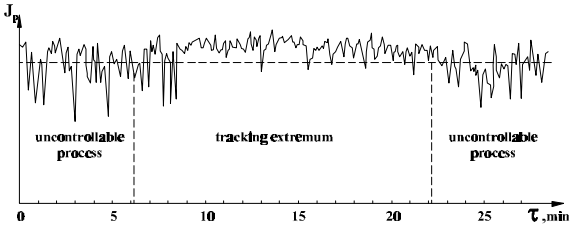

Fig.6. The process of extremum tracking by the simplex method (slow drift).

current operating point. Upon attaining the extremum and its tracking an emergency occurred on the injector qualified by the system as a fast drift. The system tried but without success to improve the situation, but with the breakdown removed, the system succeeded in 50 steps.

Another example of system operation in the extremal regulation mode (by the simplex method) under conditions of a slow drift is shown in Fig.6. Then the regulation system was switched off and already in several minutes the intensity level was decreased and dispersion was increased.

The algorithm with the RSBS method manifests itself as successful in all the above situations. But it ranks below the simplex method in speed of operation. But a lesser dispersion at the starts from current points makes it promising in the extremum regulation mode.

Experiments with application of other methods also confirm their workability, but their efficiency proved to be lower. Thus, on the basis of all characteristics in the modes of optimization and extremum regulation preference is given to the algorithm with the simplex method.

The experiment was undertaken to compare the efficiencies of manual and automatic adjustment. Once the accelerator had run into the optimal mode, as decided by an operator, the control was transferred to the computer and in the first 20 steps the intensity increased to 12%.

There was some subjectivity in the estimation of the optimization effect, since the fact of the extremum attainment was tested by manual fine-tuning. But, in any case the computer-aided adjustment is competitive with manual adjustment both in accuracy and, in the general case, in speed of operation. As for the mode of tracking the extremum, in all cases the start from a current point produces an increment in intensity and a reduction in dispersion.

It is fair to say on the basis of the investigations undertaken, that the optimization methods hold great promise for applications in the problems of control over charged particle accelerators.

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