EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PS 85-54 (OP)
October 1985

NON LINEAR OPTIMISATION TECHNIQUES FOR ACCELERATOR PERFORMANCE IMPROVEMENT ONLINE: RECENT TRIALS AND EXPERIMENT FOR THE CERN ANTIPROTON ACCUMULATOR (AA)

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ABSTRACT

The use of function minimisation techniques for optimum design according to given performance criteria is well-known. Given a well-defined criterion and a means of evaluating it precisely, the problem reduces to choosing the best optimisation procedure to suit the problem. Direct search techniques which do not generally rely on the computation of derivatives of the error function are ideal for online improvement of the global accelerator performance since the error function is not known analytically, e.g. the number of antiprotons stored in the AA ring on a pulse-to-pulse basis as a function of all the antiproton production and stochastic cooling system parameters.

The user-friendliness of the Nodal Interpreter at the man-machine interaction level, its capability easily to control and manipulate equipment as well as its capability to synchronise with respect to time events on a cycle-to-cycle basis makes it perfectly amenable to an online accelerator performance optimisation type of application. A modular procedure, based on the Simplex technique [1] has been implemented recently which permits function minimisation depending on the error function definition module. This enables an easy manipulation of variables and synchronisation with machine events.

For the AA, while the circulating beam current transformer lacks the resolution to measure the exact number of antiprotons stored on a pulse-to-pulse basis, there are a large number of electrons produced in the production process [2] and a signal emanating from these can be adapted to provide the performance criterion and appropriate parameters used as function variables in the optimisation process. First trials based on optimisation of injection of antiprotons in the AA look promising, but further work is necessary in the direct definition of the error function.

Based on the invited contribution to the 2nd International
Workshop on Accelerator Control Systems,
Los Alamos, New Mexico,
October 7-10, 1985

1. INTRODUCTION TO FUNCTION MINIMISATION AND TECHNIQUES

Performance improvement or system design by computer aided optimisation is one of the most nebulous of the techniques because the subject covers a very wide area with a host of optimisation procedures. In this context, while some of these procedures would give satisfactory results for a given problem, they would perform, surprisingly, rather poorly for another type of problem. A universal failsafe "optimiser" has yet to be found and hence numerous techniques have been developed and applied over the last twenty-five years or so to solve problems in fields wide-ranging from economics and operational research to engineering.

The optimisation or function minimisation procedures that have been developed and applied are the same, whatever the particular application and Fig. 1 illustrates the generalisation of the problem suitable for potentially all applications.

GENERAL OPTIMISATION STRATEGY

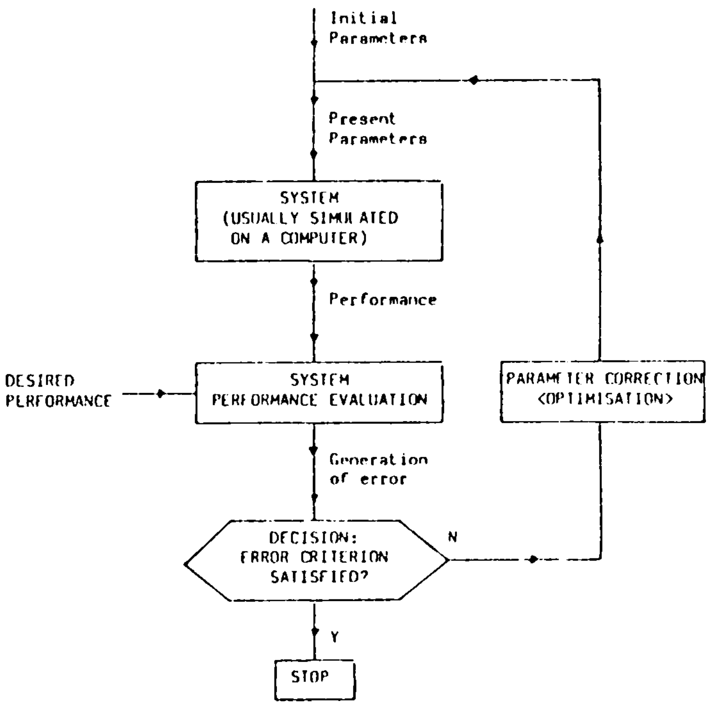

Fig. 1

The adjustable parameters are the system variables upon which depends the performance of the system; the comparison between the system performance and the desired performance yields a single number, usually called the error function, which gives a measure of system optimality or inadequacy, i.e. the "goodness" associated with that particular set of system parameters. The decision stage, therefore, judges this figure of merit and stops the whole procedure when a suitable system performance is achieved by a particular set of system parameters. If the performance is not satisfactory, the system parameters are adjusted repeatedly and the performance re-evaluated till it satisfies the pre-assigned performance requirement.

The problem of constrained (and unconstrained) minimisation are usually solved by three types of optimisation techniques, conveniently classified as simple, first-order and second-order techniques.

Simple techniques generally do not rely on the computation of the derivatives of the error function and effectively achieve the function minimisation by interpolating the behaviour of the error function in the light of certain exploratory moves.

The first and second order approaches to function minimisation both rely on the multi-parameter Taylor series expansion of the error function and involve the evaluation of its first and second partial derivatives. In the first order methods, only the first partial derivative is evaluated and the minimisation is carried out by locating the minimum along each of the parameter axes in the error space and pursuing the direction of steepest descent. In the second order method, the Taylor series expansion (up to second derivatives) is differentiated with respect to the changes in the function variables and equated to zero to locate the stationary points. This yields the necessary parameter adjustments for a minimum error in terms of the gradient and the inverse second-derivative matrices.

Both the first and second order methods are prone to long, time-consuming processes and in particular, the first-order method slows down considerably in the presence of valleys because of the one-at-a-time axial search; in the second-order techniques, the disadvantage lies in the number of computations required for the evaluation of the inverse second derivative matrix. In any case, for the online cyclic application as for the AA pbar production beam, the error function is not known analytically and even under the condition that it existed, it would need a substantial effort to apply such techniques to work every 2.4 s.

2. THE SIMPLEX METHOD OF UNCONSTRAINED FUNCTION MINIMISATION

The Simplex method locates the minimum of a multiparameter function by an ordered series of function evaluations. The method is ideal for problems where the derivatives are not easily calculable but an error function is well defined.

For a n-parameter problem, the procedure begins by specifying at least (n+1) points enclosing a non-zero volume in the n dimensional error space. The method derives its name from the resulting figure (called the Simplex) obtained by connecting these (n+1) points. Hence, for n=2, the Simplex is a triangle while for n=3, it takes the form of a tetrahedron.

The basic operations involved in the function minimisation are the selection, reflection, expansion and contraction of the Simplex vertices, based on the value of the error function at each of these points. In essence therefore, the method may be viewed as the tumbling and shrinking of the Simplex towards the minimum after a selection of vertices and their reflection and/or expansion is carried out at every stage.

3. IMPLEMENTATION IN THE PS ENVIRONMENT

The Simplex procedure has been implemented in a modular form in the PS control environment. The procedure has been written in Nodal with considerable advantages in easy access to accelerator variables both for acquisition and control. The Nodal interpreter also permits particular procedure calls through its defined function capability and allows subroutine-like calls to be made.

The error function computation is therefore done in such a defined function, which is loaded as part of the initialisation and starting values assignment module. The rest of the program is purely the Simplex algorithm and its exploratory moves based on the error function computation. Also, the specific problem of improving performance on a cycle-to-cycle basis means that timing synchronisation is necessary so that the error function computation occurs on the correct cycle after the application of the values as part of the optimisation process. This is also done in the error function computation module. Both the timing synchronisation and variable control are relatively easy to implement in Nodal, giving a great deal of flexibility in changing the function variables without any modification to the optimisation process. The procedure has been tested against some of the well-known parabolic valley functions [3,4] and agreed well with the published results.

4. APPLICATION FOR THE AA ANTIPROTON PRODUCTION BEAM

The application of the optimisation technique on a trial basis was based on the notion that antiproton production and accumulation may be maximised using relevant parameters involved in the process.

The antiprotons produced from the target and collecting horn are transported via a beam line and injected into the accumulator ring using septum and kicker magnets. The processes of precooling, RF capture and deposit, stack-tail and core cooling occur afterwards, and this constitutes the complete process of antiproton accumulation, which lasts over several hours. The first part of the sequence, from production to deposit in stack-tail region, is repeated every 2.4 s during an antiproton production run. The stack-tail and core systems run continuously to stochastically cool the antiprotons.

The antiprotons produced and stored are very small in numbers ($\approx 4 \times 10^6\ \bar{p}$ stored per pulse of 10^{13} incident protons) and the circulating beam current transformer lacks the resolution to measure the exact number on a pulse-to-pulse basis. The use of a current transformer as the performance criterion in the optimisation process is therefore not possible at the moment. Instead, a signal emanating from the large number of electrons also produced in the production process is digitised and adapted to give a number which can be considered as the error criterion.

To test the validity of the optimisation procedure, synchronisation and application online on a pulse-to-pulse basis, the initial trials have been based on a two-variable problem and these have been carried out parasitically during normal physics production runs. in the first case, the septum and kicker magnets values were optimised over several simplex iterations to yield the best production performance criterion. In the second case, the septum and a horizontal steering magnet values were varied, again to give an optimum. Fig. 2 illustrates an example of the latter, whereby the electron loss signal amplitude was reduced from 10 (before) to 2 (after) by the optimisation procedure, leading to an improvement in global performance given by the accumulation yield.

One of the occasional problems has been that the electron signal used as an error criterion fluctuates sufficiently above the threshold to make the iterations progress in wrong directions; this was proved by standard test error function application where convergence occurred without any false exploratory moves. In all the cases tried, the excursions beyond the minimum and maximum values of magnet currents were constrained by a weighted penalty.

The optimisation procedure could only be tried parasitically in the normal physics runs under strict time constraints and without affecting the antiproton production a great deal to be noticeable.

1985-09-29-12:10:30 Performance BEFORE

```
STACK 100.04E9 PBARS   ACCUMULATION YLD*1E7:  2.99
                 Normalised Accuml. Rate:  6.225E9/HR
PS-INT:15.01E12 ACCUMULATION:   6.313E9/HOUR
TFA007:14.7 E12              :  4.208E6/SHO
TFA059:14.2 E12     SUPERCYCLE  6.0/6 CYCLES
BEAM TO TARGET  96% MISSING FCTR 5.57
ECO AMPLTD;10  EL.YLD;  6.70E-7
          YIELD  AVERAGED
SUM KICK:740.19 KV
SEPTUM: 3846.7 AMP
FINE DELAY:150
```

```
)CL(AP:N-C)SIM-H-EV^C
)RU
```

Starting septum and horizontal dipole values

```
SEPTUM=  3846.97     DHZ=    -6.7033     <<<<<<STRT
 2.81000000E2    2.60000000E1    2.50000000E1          3846.97    -6.70
 2.29000000E2    2.00000000E0       <    5 >                 1

 8.00000000E1    2.60000000E1    2.00000000E0          3870.99   -10.85
 1.70000000E1    1.70000000E1       <   11 >                 2

 2.60000000E1    1.70000000E1    2.00000000E0          3870.99   -10.85
 4.90000000E1    4.90000000E1       <   13 >                 3

 4.00000000E1    8.00000000E0    5.00000000E0          3870.99   -10.85
 8.00000000E0    8.00000000E0       <   19 >                 4


ABS ERROR= 0                 IN  4.78199463E1    SECS
VARIABLES      3.86729303E3    -1.01085162E1

ITNS=     4     FUNC EVALS=    20
```

Values after optimisation

1985-09-29-12:15:35 Performance AFTER

```
STACK 100.59E9 PBARS   ACCUMULATION YLD*1E7:  3.13
                 Normalised Accuml. Rate:  6.513E9/
PS-INT:14.87E12 ACCUMULATION:   6.534E9/HOUR
TFA007:14.7 E12              :  4.402E6/SH
TFA059:14.2 E12     SUPERCYCLE  6.0/6 CYCLES
BEAM TO TARGET  96% MISSING FCTR 5.34
ECO AMPLTD; 2  EL.YLD;  6.66E
          YIELD  AVERAGE
SUM KICK:740.29 KV
SEPTUM: 3867.0 AMP
FINE DELAY:150
```

Fig. 2

5. FURTHER WORK

Further work that needs to be pursued is the elimination of fluctuations in the error signal, say, by simple averaging initially. This may slow down the process overall but is of little consequence because an error function evaluation can still be done every 2.4 s. Once the noise is reduced, the procedure is readily amenable to multi-parameter application. Incidentally, for the new antiproton collector ring under construction, it is hoped to have a circulating beam current transformer of sufficient resolution to be of direct use as a performance criterion.

The encouragement shown by E. Jones and C.D. Johnson to pursue this work and L. Henny for reading the manuscript is gratefully acknowledged.

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<u>Distribution</u> (of abstract)

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