Power-Nuclear Plants

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POWER - NUCLEAR PLANTS
COMMENTATOR'S REPORT - SESSION 6

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1. INTRODUCTION

This session consists of six contributions. Five of them treat the problem of power control in nuclear reactors. The sixth paper considers the dynamics of a coolant channel in a gas-cooled reactor.

The report is divided into two parts. In the first part a brief survey is made of some problems appearing in power reactor control. The contributions of the session are introduced there from this general point of view. In the second part each paper is discussed and reviewed separately in more detail.

Three of the papers (Moore-Schweppe, Bereznai-Sinha, Atary-Shah) use space independent models, and the purpose is control of total power or mean neutron flux. Two others (Stark, Grumbach) consider distributed systems with one group diffusion models. In the analysis they discretize or use modal representations in order to obtain lumped parameter systems. All five papers apply Linear-quadratic control theory. In some of the papers system parameters are estimated using least squares, the Maximum Likelihood method or Extended Kalman filters.

The word "application" is used for many different types of contributions. In one case it really means control system implementation on a real plant (Grumbach). For other authors it means a use of real experimental data for analysis or test of a model (Atary-Shah). Application in the sense of simulation studies and tests has been used in one paper (Moore-Schweppe). Taking models from literature or theoretical analysis of reactor plants is also called application (Bereznai-Sinha, Stark).

The paper by Eigner is not discussed, since the available documentation does not give a sufficient base for a relevant judgement.

2. SOME PROBLEMS IN POWER REACTOR CONTROL

2.1 General background

Since the first commercial power reactors were installed in 1956, a tremendous development has taken place. Nuclear power is getting a significant part of total power production in many contries. This development has caused new demands on the nuclear plants as far as control is concerned. The plants are used not only for base load production. Load following capabilities are important. Power companies now demand load following characteristics corresponding to a power change of 20-30 % or more per minute until say 30 % from the nominal power.

When the power units are made larger, however, stability problems also increase. Spatial stability is a function of geometrical dimensions, and stability problems occur, when the core gets much larger than the neutron migration length. Distributed models therefore get more interesting also for control purposes.

It is plausible, that thermal reactors will be built as the major power producer until the end of this century. The control problems for this type of process will therefore be even more important in the near future.

2.2 Model building

From a dynamical point of view the plant can be considered made up by two parts, the nuclear core and the heat removal circuits. The latter parts cause the same type of control problems as in a conventional steam boiler plant.

For the purpose of power control it is essential to consider both these parts of the plant. The whole plant is a very complex dynamical system. In order to find reliable models for control purposes, the goal of the control must be made clear in order to find reasonable approximations.

The problem of suitable model complexity is difficult. How complex models are needed for a certain closed loop accuracy? This problem is not solved generally, why the models have to be tried out experimentally. The general problem of model building for control has been discussed elsewhere(1).

An essential question is the time horizon for the control. The plant dynamics include time constants from less than a second to several days. The time constant for the neutron kinetics is only a fraction of a second. It is some or a few seconds for the heat diffusion in fuel and in the coolant channel dynamics. On the other hand the reactivity coupling between the heat removal circuits and the core give rise to dynamics with time constants of the order some minutes.

Reactor poisoning effects due to xenon and samarium cause power variations over several hours. Burn-up depletion of the fuel must be taken into account for a period of some week.

The very slow equations can be considered as time variable reactor parameters. A model, where only the kinetics and heat flow in the core are present normally cannot be considered time invariant over a period of several days.

The influence of a certain mode is not only depending upon its time constant. One has to take its amplitude into account in order to decide, where the influential dynamical modes are situated.

Another problem is due to nonlinear phenomena. If the power variations are large (e.g. at load following) either a nonlinear model or a time variable linear model must probably be used. A time invariant linear model might give erroneous control.

If the purpose of the control is to minimize power variance around a certain nominal level, it is important to build a disturbance model. Few such models are available.

Spatial effects will be more influential, when the plant sizes increase(2,3). Distributed models, however, are in general very complicated, and therefore no real reactor control implementation has been reported. On the other hand, lumped models are still relevant for many reactor types, and spatial discretizations are common.

Grumbach has treated the problem of neutron flux distribution control in order to achieve e.g. a desirable power profile. Stark has analysed a similar problem with some different technique. The time horizons are quite different. Grumbach uses a sampling interval of a few minutes, while Stark has a one second interval.

Many different model building approaches have been used in the papers. One extreme of model building technique is represented by Atary-Shah. A very detailed and complex model has been constructed from physical considerations and plant construction data. The model has been reduced to a linear and relatively small order process.

The other model building technique is identification, where no physical á priori model is assumed. The parameters are directly adjusted to measurement data(1). This type of off-line identification approach with Maximum Likelihood criteria has been used with success for nuclear reactors before(4).

One of the contributions (Bereznai-Sinha) describes an identification of a simple deterministic second order model from a larger one. No physical assumptions are made. A least squares criterion is used.

In the papers by Grumbach and Moore-Schweppe more refined techniques are applied. The authors include an on-line identification scheme, where physical á priori assumptions are made. Because of the structural assumptions, parameters of multivariable systems can be identified. Grumbach uses a least squares method, and Moore-Schweppe use a combination of least squares and a Maximum Likelihood approach, developed by Schweppe(5).

This on-line identification is then used as part of an adaptive control strategy.

In the literature other methods are applied to find reactor parameters on-line. Extended Kalman filter has been used for simultaneous parameter and state estimation(6). Different types of least squares criteria have also been used for sequential parameter estimation(7,8).

Only Moore-Schweppe use any systematic method to find any plant disturbances and measurement noise model.

2.3 Power control

In all papers of the session the control purpose is either constant total power (mean flux) or both desired total power and power distribution. The performance index is assumed quadratic. Most authors have chosen the index by trial and error.

Grumbach has used an iterative method, tailormade for the certain process, to get the state weight matrix of the performance index. The matrix is assumed diagonal. By a suboptimal Linear-quadratic control law the next state value is calculated. If the constraints then will get violated, the weight matrix is iteratively adjusted until the predicted state is satisfactory.

Optimization theory has been used extensively on nuclear reactor models. Control of a reactor from one to another operating point in minimal time has been examined by nonlinear optimization theory(9). The Maximum Principle has also been applied to a quasi-linear system to obtain time optimal control(10). The same problem has also been solved by Dynamic Programming(11). Linearizing approximations have been performed to investigate on-line optimization of reactor power control(12). Linear-quadratic theory has also been used by other authors(13) with different types of approximations, and it has been applied in investigation of start-up problems(14). Control laws of the Linear-quadratic type have been implemented on the Halden BWR(15), which is a well instrumented experimental power reactor.

2.4 Adaptive control

A nuclear reactor is a typical example of a system having unknown time variable parameters. It is necessary to continuously update the parameters, sometimes in some seconds or minutes at a load change, sometimes less rapidly during xenon oscillations or burn-up changes of the fuel.

In an adaptive control system the control is applied simultaneously as real time identification of the parameters. Strict separation between identification and control has been assumed, and no dual control in the sense of Feldbaum(16) has been applied.

Adaptive control has been considered before(17) to improve reactor performance. It has also been examined in a nuclear rocket engine control problem(18), where the proportional control gain was the parameter adjusted.

Moore-Schweppe use adaptive control in the sense given above. The system parameters must be updated e.g. because of load changes. Two methods are used for the updating procedure. A least squares estimation gives a first approximation and an initial condition for the Maximum Likelihood identification(5). The latter method is not used recursively, because old data must be stored. The combination of stochastic multivariable modeling with identification and Linear-quadratic control is assumed to be new as a reactor application.

Grumbach has another purpose of control. The power distribution shall be controlled to a desired profile by the absorbtion rods. The parameters are identified in a straight-forward manner using least squares. The sampling time, a couple of minutes, is between the rapid transients and the slow variations, caused by reactor poisons. The identification is therefore performed by calculating the partial derivative of the remaining change of the state with respect to corresponding control variable change. The control is performed with a suboptimal Linear-quadratic law.

Bereznai-Sinha make much a simpler approach. The reactor is represented by a second order model. The adjustment is made to the step response of a larger deterministic model, but no recursive technique is reported in the paper.

3. COMMENTS TO THE INDIVIDUAL PAPERS

Each paper is commented on below separately in the order it appears in the conference program.

3.1 Adaptive control for nuclear power plant load changes (R.L. Moore and F. Schweppe)

The authors have used an adaptive approach to control a reactor plant during load changes. A sixth order stochastic model has been developed, based on a 23rd order nonlinear PWR model. The low order model has been identified from the large order one by a Maximum Likelihood technique, and it is the base for a linearized Kalman filter estimation and Linear-quadratic control. The method has been tested by hybrid simulation, where the real process was represented by the mentioned 23rd order model.

Plant model

The sixth order stochastic model of the reactor has been linearized around the nominal trajectory. The authors have not further motivated the choice of state variables. Relatively fast modes, such as delayed neutrons as well as water temperature and turbine dynamics are represented. It might, however, also be relevant to treat the heat removal circuits more carefully, because of their time constant and influence upon the plant behaviour. Xenon and iodine equations are included in the model. The ratio of the largest to the smallest time constant in the model is more than 10^4. Therefore it might be very difficult to find a reasonable sampling time for the system. The xenon concentration can also be considered as a slow time variable parameter. Alternatively, it could be suitable to use a hierarchical structure to control the different modes.

The choice of model order is not self-evident. The simulations indicate, that the control strategies based on the actual model can control the complex system in a reasonable way. There is, however, no discussion whether the model could be simplified even further or if improved performance could be achieved with strategies computed from a more complex model.

Additive noise is introduced to represent process disturbances as well as model errors. The choice of noise characteristics is a difficult one. The authors´ assumption of zero mean noise is crucial. The mean value might be considered as an unknown parameter.

Parameter identification and plant control

The identification and the control phase are separated. The stochastic model is used to predict the nominal trajectory and the variations around it, when the disturbances are taken into account. As the nominal predictions and the constraints are displayed an operator can easily judge, if any constraint will be violated during or before a load change.

Two identification methods are used. The initial parameter estimation is achieved by a least squares method, and after that a Maximum Likelihood method is used for a more accurate identification. This method is used off-line in the present work.

Maximum Likelihood technique has been used extensively by other authors with different model structures(1,19). One advantage with the Moore-Schweppe method is, that the asymptotic Kalman filter gain is achieved simultaneously. This is also well known. The technique assumes, that the parameter vector varies slowly as compared to the state variables. Otherwise the filter can diverge easily.

The authors state, that the computing times probably can be improved. The state equations are linearized in every step, and that procedure is of course time consuming. It can be mentioned here, that the same number of parameters in a linear structure, suggested by Åström(20), is identified more than 50 times faster with corresponding computer(19).

The authors also found, that the Maximum Likelihood technique sometimes was sensitive for the model structure. It would be interesting to know, if this effect is caused by numerical problems, or if it has to do with the "degree of parameter observability"(21).

One identification result is shown in table 1 of the paper. Some "g" parameters are very small. It must be quite easy to calculate the parameter estimate variance. If this one is taken into account, are all the mentioned parameters significantly different from zero?

It is not described in detail, how the off-line Maximum Likelihood estimation and the on-line least squares technique are combined with the optimal control. The calculation time to find a revised model and a new Kalman filter by the Maximum Likelihood method is not negligible. During that calculation the model can change significantly, and the corresponding old Kalman filter and control might give erroneous results. Did the approximative on-line parameter adaptation give satisfactory results in the closed loop system? It is well known, that a switch between different strategies can often lead to difficulties. It is not discussed precisely, how this is handled in the paper.

At a load change it is plausible, that several parameters are changed. In figure 6 of the paper one case is displayed, when only one parameter is changed. It would be interesting to know, how the method works in the case of several time varying parameters.

3.2 Optimal feedback control of a Pressurized Water Reactor (K. Stark)

A deterministic model of a PWR has been investigated. The purpose is control of total power (represented by mean flux) as well as neutron axial distribution to a desired profile.

The diffusion equation is analysed by modal analysis. Hereby the theory of lumped systems can be used, and the modes are assumed independent.

The model is, however, quite insufficient, and some quite unrealistic assumptions are made, e.g. a coupled spatial modal system is used, and it is assumed direct measurements of fuel and coolant temperatures. This makes the demonstrated control strategy difficult to apply to a real power reactor.

The axial spatial effects are assumed to be the only spatial variations. Such an absorbtion rod configuration is assumed, that makes the axial flux distribution controllable. The controllability for such systems has been considered elsewhere(2).

Only the core has been modeled and the heat removal circuits are not considered. This is not realistic.

The diffusion equation is evaluated into modes, viz. sine waves. These functions are not independent for power reactor systems, in contrast to the author´s assumption(22). Therefore it is not correct to assume a decoupled control system.

The author also claims, that fuel and coolant temperatures can be measured directly. This assumption implies, that the temperature dynamics can be neglected, and only the kinetic equations remain. The latter are bilinear equations. The bilinear term is replaced by a fictitious control variable, and a linear problem is achieved. The same method has been used previously(23,24).

Some difficulties arise because of this replacement. In the performance index the fictitious variable appears as the control variable, and sometimes it might be difficult to find a suitable weight coefficient and a relevant physical interpretation. In order to get the real control variable, one must also know the neutron density, which is a problem in itself.

3.3 Application of optimum low-order models to the adaptive control of nuclear reactors (G.T. Bereznai and N.K. Sinha)

The purpose of this work is optimal control of the total power of a 200 MW heavy water reactor. In order to achieve this control a deterministic second order model is used. It is found by successive adjustment to a ninth order deterministic model of the actual reactor plant.

The authors state in the introduction that "the research efforts presented to date invariably assume an over-simplified representation of the reactor kinetics, typically the one delayed group model...". It seems to me, that a number of over-simplifications have been done also in the present paper.

It has not been shown, that the actual control law is relevant for a real plant. It is believed, that the purpose of the contribution is to show a certain model reduction method, applied to a special reactor example.

The basic model has the order nine. It is used as a reference, and therefore it ought to be considered more carefully. The neutron kinetics is represented by seven states, neutron density and six delayed neutron groups. This makes the kinetics over-represented as compared to other dynamic parts of the plant, that might be more important in control applications, such as coolant dynamics, hydraulics, heat removal circuits and turbine dynamics. The temperature feedback is represented by a simple first order equation, and the absorbtion rods represent the last state variable.

It is also assumed, that the neutron density can be measured instantly and without disturbances. This deterministic approach is crucial for the method.

The purpose of the control is not precisely formulated, but is believed to be nuclear power control (mean flux control) at steady state. The reason for the choice of model order seems to be, that the Linear-quadratic feedback equations are especially attractive in this case.

The feedback coefficients are held constant during ten sampling intervals, and during that time the low order model is updated to the high order model response by a least squares method.

3.4 On-line computer control of the neutron flux distribution in a nuclear reactor core (R. Grumbach)

The problem of flux distribution control is attacked by in principle Linear-quadratic theory. The space dependent variables are discretized in space, and therefore lumped parameter system theory can be used. The purpose of the control is to follow total power demand and to control the power distribution in the core close to a desired profile.

Neutron flux model

The author has defined the time scale for the control, partly by physical considerations, partly by computer restrictions. It is not realistic to make a faster control than some minute sampling interval. During that time the fast transients, such as neutron kinetics, heat flux dynamics in fuel and coolant channels are considered converged. The slow variations like xenon poisoning and burn-up effects are approximated as static equations or very slow disturbances. The reactor differential equations get simplified by these assumptions.

The author postulates the time discrete dynamics

$$x(k+1) = I\,x(k) + C(k)\,u(k) + e(k)$$

where I is the identity matrix. In this application the dimension of x is larger than that of u. The state vector represents the neutron flux in a number of space points. The disturbance vector e is not given any statistical interpretation, but is considered simply as an error term at the model adjustment.

This model is strange, because it is obviously not controllable. It is not even asymptoticly stable. Consequently it is impossible to find a control law, such that the flux values can be controlled to arbitrary values. It would have been more appropriate to describe the coupling between the local fluxes, due to the neutron diffusion, in a system matrix.

The rectangular matrix C is updated by measurements. It is determined from the partial derivatives of the remaining change of x with respect to the change of the control rods u. Then two conditions must be satisfied. One condition is, that the control amplitude is large enough, such that the partial derivatives can be calculated with some degree of accuracy. The other condition is, that the disturbances must be assumed small.

It is also assumed that all state variables are directly measured, which demands a large number of detectors in the core. This is realistic for the Halden BWR, as it is relatively well supplied with instruments.

In order to eliminate the influence of disturbances a large number of observations are performed, and a least squares method is used to find the C matrix. It is not stated, that a recursive least squares method is used, but that should be suitable here.

In control of local flux distribution the power in the coolant channels is the interesting variable. As in the present paper, this local power has to be estimated by detectors, placed outside the channel. This estimation is not at all simple. Especially in a BWR the local power may vary abruptly from one channel to the next one, because of different burn-up values of the fuel elements. This means, that a very fine structure model of the core is needed in most cases, when handling such estimation problems. The dimensionality of the problem thus can explode very easily.

Flux control

The author suggests a suboptimal solution of the Linear-quadratic control problem, one step optimization. This approach has been used elsewhere(25). It makes it possible to simplify the calculations considerably. On the other hand it is difficult to know how far this suboptimal solution is from the optimal one.

The experiments showed, that the system is not completely controllable. It was impossible to change all state variables simultaneously to arbitrary values, but only within the controllable subspace. By changing the performance index the author showed, that certain state variables could be moved, within the controllable space, more or less close to the desired values.

Grumbach presents an attempt to systematicly find a suitable performance index. The weight matrices are functions of the safety margins of the state variables. The state variable weight matrix Q_1 is assumed to be diagonal. Q_1 can be changed iteratively if it is found, that it will cause the constraints to be violated. After Q_1 is corrected the control variable weight matrix Q_2 is adjusted iteratively.

The method is not general, because practical experiences have been necessary in order to find the suitable correction of Q_1 in every iteration.

3.5 Modeling and analytical control system design of a complete nuclear power plant prototype (J. Atary and M.M. Shah)

In this paper emphasis has been turned upon two different ideas, model building and suboptimal estimation and control. The latter part should be considered from a general point of view, and the reactor model is only a special application of these ideas.

Model building

A complex model of a 200 MW PWR was derived by Atary in an earlier contribution. The model consists of 220 nonlinear differential equations, and in the paper it is quoted as "valid within the range of ± 15% of full power".

Such a model is naturally at present unrealistic to use for control purposes. Therefore it has been reduced by the authors, in two steps.

In the first stage it was reduced only from physical considerations and experience. In the next step a systematic method was used, which is based on the eigenvalues of the system(26). The final model is of order 18 and is linear.

Also in this reduction stage, the authors have used the special structure of the plant. Otherwise the proposed reduction method did not work, because of the large differences in the plant time constants. The plant was divided into six subsystems.

It is not clear, however, that it is necessary to represent every subsystem in the control model. A certain subsystem might be neglected completely from this dynamical point of view. Probably the model order might be reduced further, without causing too inaccurate a control.

For system reduction in another reactor application also factor analysis(27) has been used.

The model seems to be unsatisfactory in the sense, that although the deterministic parts are modeled with an 18th order system no disturbances have been modeled. Only heuristic assumptions have been made, and the disturbances are described as white noise forcing functions.

The model is time invariant and linear, and therefore its validity is limited. Very slow changes in the parameters due to poisoning and burn-up might cause large errors in the long run.

Estimation and control

In the second part of the work a special suboptimal method for Kalman filtering and Linear-quadratic control is presented. Even if the technique is independent of the reactor model, the special structure of the plant has been used.

In Kalman filtering a large computing capacity is needed for complex and high order processes. In the actual case the plant is divided into a number of subsystems, and every subsystem has its own Kalman filter. The noise terms in the suboptimal filter then consist of two parts, the real noise and a linear combination of the noise and estimation errors from the other subsystems. One crucial assumption is, that this noise is white. Dr. Shah claims that this is a reasonable approximation.

It would have been interesting to see a comparison between the optimal and the suboptimal filters.

In this special application it is also assumed, that the process and measurement noise from one subsystem do not influence any other subsystem.

In some cases the suboptimal solution was shown to give even better results than the "optimal" one, which seems too good to be true.

The sampling interval is chosen 0.1 second. This is a very short time, when calculation times for the filter and the control are considered. It might be possible to consider the kinetic equations prompt and use a longer sampling interval.

4. CONCLUDING REMARKS

There are still several problems how to find relevant plant models for different control purposes. Adaptive control is an attractive tool, when considering load changes and slow parameter variations, The problem of real time recursive parameter updating in combination with optimal control is not yet satisfactorily solved.

Because of the large differences in plant time constants, hierarchical control should be subject for future studies.

Finally, an application is not considered complete before it has been implemented on a real plant. Many problems of that nature still remain also after IFAC 1972.

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