CONF-810701--7

THE UTILITY OF LOW-ORDER LINEAR NUCLEAR-POWER-PLANT MODELS IN PLANT DIAGNOSTICS AND CONTROL

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CONF-810701--7

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ABSTRACT

A low-order, linear model of a pressurized water reactor (PWR) plant is described and evaluated. The model consists of 23 linear, first-order difference equations and simulates all subsystems of both the primary and secondary sides of the plant. Comparisons between the calculated model response and available test data show the model to be an adequate representation of the actual plant dynamics. Suggested use for the model in an on-line digital plant diagnostics and control system are presented.

INTRODUCTION

With the recent incidents at Three Mile Island and other facilities, there is a renewed interest in the protection and control of nuclear power plants. Specifically, much attention is being paid to the problem of supplying the plant operator with the information needed to properly ascertain the plant status. The current approach is to use digital computer-generated CRT color graphics to display plant measurements. A straightforward improvement to this approach would be to somehow process the plant measurements, using the digital computer, to test the validity and accuracy of the measurements before displaying them on the CRT. This pre-display processing could be something as simple as a low-pass filter or as detailed as a set of optimal estimation and control algorithms. The point is that as long as the digital computer is in the control room driving the color graphics, why not use it to provide better information for the operator.

One possible signal processing method would be to implement a small on-line dynamic model of the plant. This model could be used to check the consistency of the plant measurements being taken and alert the operator to any anomalies noted. Such a model could also be used to predict the plant response to proposed operator control actions or could be used in a Kalman filter to provide optimal estimates of critical plant variables (1). Under a Department of Energy sponsored program, such a model of a pressurized water reactor plant has been developed and evaluated. The model developed is specifically of the LOFT (Loss-of-Fluid Test) reactor located at the Idaho National Engineering Laboratory. The LOFT plant, shown schematically in Figure 1, is a scale model of a pressurized water reactor (PWR) and can produce 50 MWt. The plant is used to study the engineered safety features of a commercial PWR during postulated loss-of-coolant accidents and anticipated operational transients. Due to its similarity to a full-scale plant, the linear model of LOFT described herein could easily be modified to represent a commercial PWR.

The current model is a discrete, linearized representation of the nonlinear LOFT plant dynamics. The advantages of a linear model as opposed to a nonlinear model are a simpler formulation, much faster time propagation, and the ability to directly apply optimal estimation and control theories. The linear model simulates all major subsystems of the LOFT plant, including the reactor kinetics, core thermal, primary loop thermal transport, pressurizer, steam generator, air-cooled condenser, and feedwater system. The accuracy of the model has been validated by comparing model predictions to actual LOFT transient data obtained during power range testing and subsequent nuclear experiments.

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MODEL DESCRIPTION

The current LOFT linear plant model consists of 23 first-order state difference equations and 17 algebraic measurement equations of the form:

$$\delta x(k+1) = \Phi\, \delta x(k) + \Theta\, \delta u(k) \qquad (a)$$

$$\delta y(k) = \Gamma\, \delta x(k) + \Lambda\, \delta u(k) \qquad (b)$$

where $\delta x(k)$ is the plant state vector deviation from nominal, $\delta u(k)$ the deviation of the plant control vector from nominal, and $\delta y(k)$ the plant measurement vector deviation from nominal. The matrices Φ, Θ, Γ, and Λ, are shift-invariant system matrices based on the plant nominal operating point. Unfortunately, the dynamics of a nuclear power plant and its supporting subsystems are continuous and highly nonlinear, making direct derivation of a linear, discrete model extremely difficult. Thus, it is convenient to first derive the nonlinear plant model and then numerically linearize and discretize it about some operating point to obtain equations such as (a) and (b).

The nonlinear model upon which this linear LOFT model is based is described in some detail in Reference (2). The model consists of 23 first-order nonlinear differential equations which describe the dynamics of the complete LOFT plant, as shown in Figure 1. Standard time-dependent point kinetics with two delayed neutron groups are used to model the power generation within the nuclear fuel. Reactivity sources include changes in fuel temperature, primary coolant density, and control rod position. An average fuel rod with a single fuel node and a single cladding node, separated by a variable width gas gap, constitutes the model describing the transfer of the heat within the fuel, to the core coolant.

The primary coolant loop is divided into five nodes to model the transport of heat from the core through the loop. These five nodes include the core, core bypass, hot leg, steam generator primary, and the cold leg. Provisions for direct heat deposition into the core and core bypass coolant are made in the model. The pressurizer, which acts as a surge tank to maintain primary loop pressure, is modeled as a homogeneous, saturated, fluid system, with surge flow being calculated based on the instantaneous mass change in the primary loop.

The LOFT steam generator is a vertical, U-tube, recirculation type similar to those used in most pressurized water reactors. Its dynamics are modeled by assuming the steam and water in the generator shroud region are in a homogeneous, saturated mixture, with mass and heat balances on this mixture yielding two of the desired state equations. Separate mass and energy balances on the water in the downcomer region are used to provide accurate predictions of steam generator water level. The dynamics of both the main steam control valve and the feedwater flow valve are modeled.

The steam flow from the steam generator goes directly into the condenser which is cooled by a bank of six variable pitch fans. A single state equation models the condensation process. A model very similar to that of the pressurizer is used to model the dynamics of the condensate receiver, which is simply a large collection tank. Finally, a constant amount of feedwater subcooling, needed to maintain the net positive suction head requirements of the feedwater pump is assumed.

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The resulting continuous nonlinear equations are in the form:

$$\dot{x} = f(x,u) \quad (c)$$

$$y = g(x,u) \quad (d)$$

Using standard linearization techniques (1), i.e., expanding (c) and (d) in a Taylor series, retaining only the linear terms, and then evaluating the resulting derivatives about a nominal operating point, will transform the nonlinear equations into the continuous, linear equations:

$$\delta\dot{x} = F\ \delta x + G\ \delta u \quad (e)$$

$$\delta y = \Gamma\ \delta x + \Lambda\ \delta u \quad (f)$$

Then applying established discretization methods (3) allows these equations to be cast in the desired form seen in equations (a) and (b).

TEST DATA COMPARISONS

If the linear LOFT model, described in the previous section, is to provide accurate operator information, it is important that it be a valid representation of the dynamics of the actual plant. To validate the accuracy of the model, its calculated response was compared to several sets of data obtained from the LOFT plant. Four operational transients run during the LOFT power range testing sequence (4) and a loss of feedwater transient in experiment L6-5 (5) were selected as the basis for this comparison. One of these transients, a steam generator water level controller setpoint step is presented here.

During power range testing, as a test of the performance of the steam generator water level controller, step changes in the level setpoint are implemented and the plant response recorded. Figures 2 through 5 display the LOFT response and the predicted response of the linear model to the first phase of testing, an 8 inch decrease in setpoint. The plant was at 50% power (25 Mwt) prior to the change in setpoint.

An examination of the actual plant level response, shown in Figure 2, shows that the steam generator water level drops to the demanded value of 113.8 inches, with a slight overshoot, within approximately 30 seconds. The decrease in level setpoint causes an immediate closure of the feedwater valve by the level controller and once the demanded level is attained, the feedwater valve reopens, as seen in Figure 3. The effect of this perturbation on the primary side of the plant is shown in Figures 4 and 5. The decrease in available feedwater results in a heating of the primary coolant (Figure 4) which decreases reactor power, by way of moderator density feedback, as noted in Figure 5.

A comparison of the linear LOFT model predictions of the response of the primary side to the level setpoint change with actual plant response shows that the model predicts a slight delay in the temperature increase and a somewhat steeper decline in power. The model and plant secondary response compare quite well as noted in Figures 2 and 3. The only differences here are a slight error in initial steam flow, and a faster restoration of feedwater flow by the linear model. The discrepancies between the model and plant are not significant; in fact, the linear model seems to provide an excellent representation of the LOFT plant dynamics.

It should be noted here that the water level setpoint step transient displayed in Figures 2 through 5 represents a relatively small perturbation on the LOFT plant and hence the linear model was able to predict it quite well. In a more severe transient, where the plant would be perturbed far from the operating point upon which the model is based, a fixed linear model may not be adequate. To overcome this inadequacy, it would be necessary to have the on-line capability to generate a new linear model when it has been determined that the plant has moved sufficiently away from nominal. When to perform such a relinearization of the plant model is currently under study.

MODEL APPLICATIONS

In this section, several applications of linear models in proposed nuclear power plant diagnostics and control systems are briefly discussed.

As part of a program at the Idaho National Engineering Laboratory, the linear LOFT model just described was used in a Kalman filter based advanced plant protection system (6). The system processes available plant measurements and generates optimal estimates of such critical variables as fuel and cladding temperatures, DNBR (departure from nucleate boiling ratio), and MLHGR (maximum linear heat generation rate). Simulation studies showed that comparing these estimates of variables directly related to plant integrity with limiting values to determine if a plant scram is needed, as opposed to the current technique of comparing noisy plant measurements to pre-established setpoints, could result in improved plant safety and availability. This same model was used as the basis for developing a PWR closed-loop optimal control strategy that provides fast and stable plant response during a wide variety of simulated operational transients.

Linear models incorporated in Kalman filter estimators can also be used as an integral part of instrument failure detection schemes. The functional redundancy technique employs a bank of Kalman filters and by performing consistency check between the output of each filter, failed instruments can be identified. Using a linear model of the LOFT pressurizer, it has been shown that functional redundancy can be used to detect many types of failures in measurements of pressurizer pressure, water level, and vapor space temperature (7).

The generalized likelihood ratio (GLR) method is another possible failure detection scheme. In the GLR, the innovations sequence (the difference between the actual and estimated plant measurements) of a Kalman filter designed for the unfailed system is continually tested for "whiteness". Any significant deviation of the innovations from a white sequence will result in a failure declaration. The GLR technique provides information as to which instrument has failed, when it failed, and what the estimated failure magnitude is. Preliminary studies using a linear LOFT pressurizer model have demonstrated the GLR method yields extremely accurate results in estimating biases in the pressure and level instruments (8). Other work currently underway at the Idaho National Engineering Laboratory concerned with the GLR approach includes an instrument failure detection system for the LOFT steam generator and using GLR as the basis for on-line model validation.

Other applications for linear plant models include using them to allow the capability of on-line trend predictions based on the current plant state (9) or, as mentioned earlier, by running the model faster than real-time, allow operator inquires regarding the consequences of proposed control actions.

CONCLUSIONS

It has been shown that linear PWR plant models can provide excellent representations of the actual plant dynamics. The problems associated with being restricted to linear models can probably be eliminated by having the capability of relinearizing the model as it deviates from its operating point. Such linear models when implemented on-line can provide a fast and accurate plant diagnostic tool.

ACKNOWLEDGEMENT

This work supported by the U.S. Nuclear Regulatory Commission, Office of Reactor Safety Research under DOE Contract No. DE-AC07-76ID01570.

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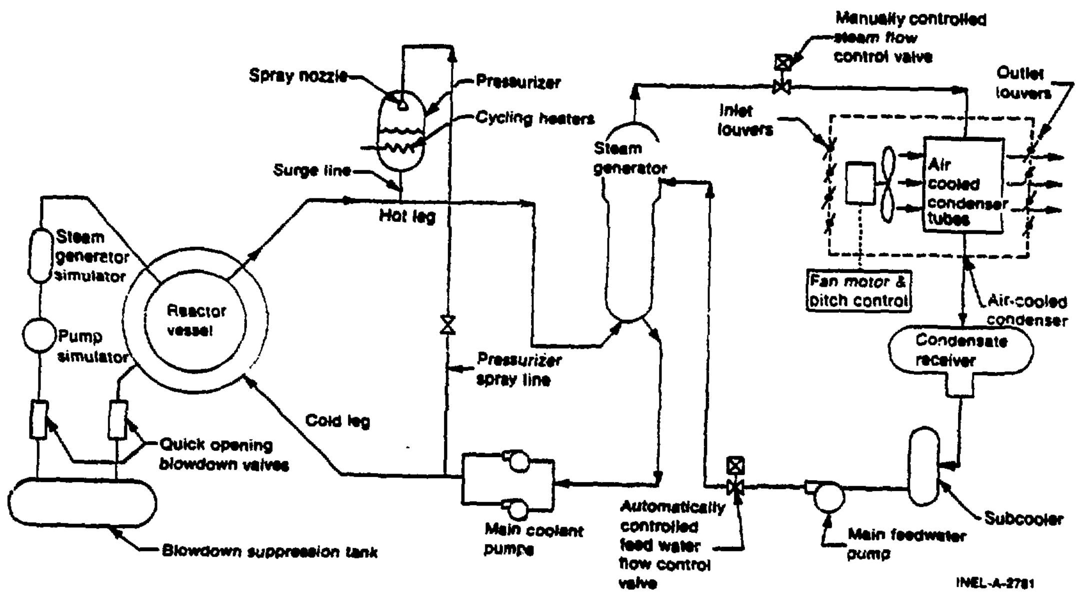

Figure 1. LOFT reactor plant schematic diagram

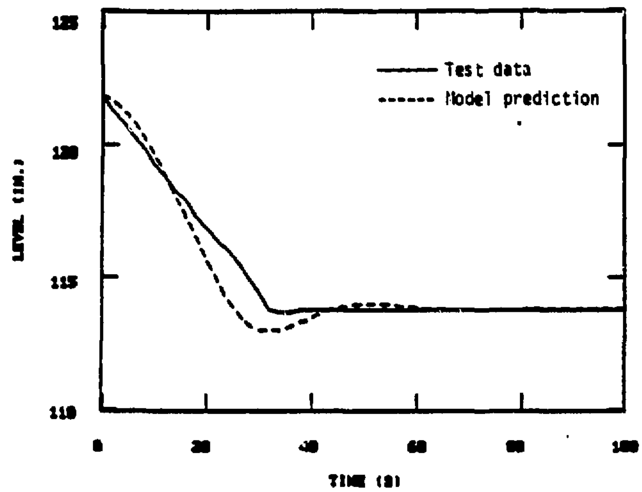

Figure 2. Steam generator level setpoint decrease, 50% power
Steam generator water level response

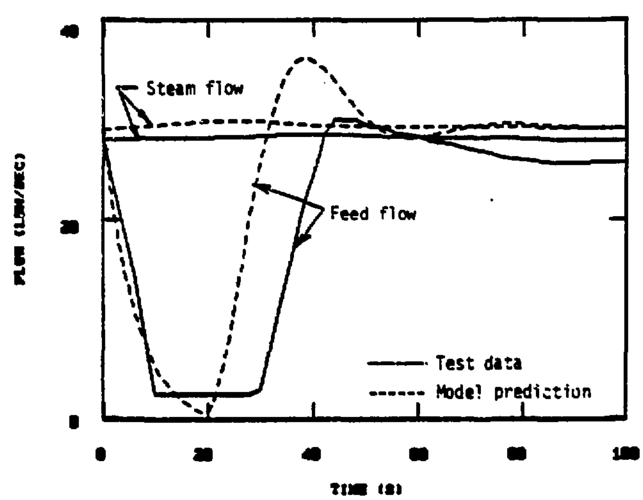

Figure 3. Steam generator level setpoint decrease, 50% power
Secondary steam flow and feed flow response

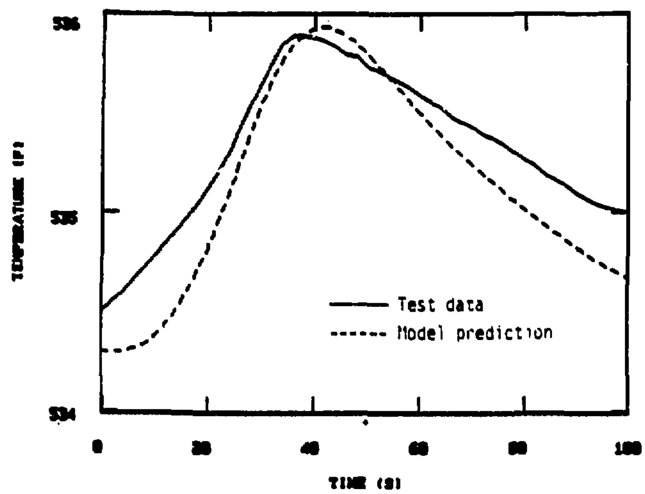

Figure 4. Steam generator level setpoint decrease, 50% power
Reactor inlet temperature response

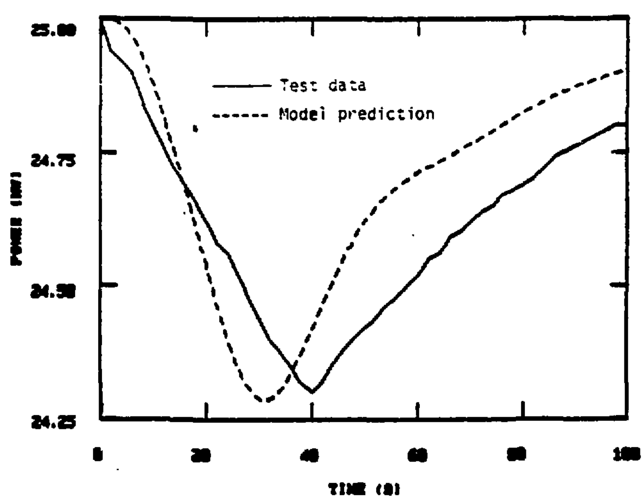

Figure 5. Steam generator level setpoint decrease, 50% power
Reactor power response