PNC TN941 81-116

Simulation Study of Neutronic and Acoustic Methods of Boiling Detection

IAEA–IWGFR

Specialists' Meeting on
"Sodium Boiling Noise Detection"

9-11 June 1981

Power Reactor and Nuclear Fuel Development Corporation

PNC TN941 81-116

9-11 June 1981

Simulation Study of Neutronic and Acoustic Methods of Boiling Detection

J. Shimazaki*, Y. Fujii*
Y. Shinohara*, H. Araki**

Abstract

As a part of the work on the development of a diagnostic system for detecting anomalies in the core of a fast breeder reactor, a study is being made on the methods of detecting abnormal reactivity and coolant boiling on the basis computer simulation. The objective of the present simulation study is to obtain some basic information useful for developing sensitive method of signal processing suitable for boiling detection.

Neutronic, acoustic and measurement noises as well as reactor kinetics and reactivity estimator are simulated on a hybrid computer and analyzed for various noise conditions using correlation, spectral and coherence analyses. It has been confirmed that the cross-spectral and coherece analyses between neutronic and acoustic signals are effective method for boiling detection provided that the void coefficient of reactivity is sufficiently large and that detection capability is slightly improved by using a discriminator of signal level before making spectral analysis.

A simulated boiling detection experiment using a zero power thermal reactor is also planned in order to check the validity of computer simulation.

---

* Tokai Research Establishment
Japan Atomic Energy Research Institute

** Oarai Engineering Center
Power Reactor and Nuclear Fuel Development Corporation

1. Introduction

Monitoring of operational state of the reactor core is very important in order to assure nuclear safety of reactor operation. The necessity of instrumentation system capable of detecting reactivity anomaly and abnormal coolant boiling in nuclear reactor core was strongly recognized by the accident of Enrico Fermi reactor and, more recently, was emphasized again by Three Mile Island accident in 1979.

Within the framework of R & D program of instrumentation and control system for a prototype fast breeder reactor now under development by Power Reactor and Nuclear Fuel Corporation (PNC), a study has recently been started on the methods of detecting abnormal reactivity and coolant boiling. The first step of this study is based on computer simulation to investigate methods of signal processing suitable for accurate estimation of reactivity and sensitive detection of coolant boiling before proceeding to experimental works.

An advantage of computer simulation study from the view point of signal processing problem in boiling detection is that various conditions of useful signals and useless noises can easily be simulated by using the signals generated based on physical models and partly the signals recorded at actual experimental facilities and operating reactors as well. Especially in the acoustic boiling detection problems where the signal to noise conditions are usually much different from reactor to reactor, computer simulation is very convenient way to study basic signal processing problems common to a variety of signal and noise characteristics before proceeding to reactor dependent application. However, if the model used in the computer simulation is not accurate enough to be fully relied on, it is necessary to make experiment in order to check the validity of simulation study.

In this paper will be described very briefly the scope and the examples of preliminary results of the study being performed for the development of reactivity anomaly and coolant boiling detection at Japan Atomic Energy Research Institute (JAERI) under the contract with PNC.[1,2]

2 Core Anomaly Detection System

A simplified block diagram of the core anomaly detection system which is now being studied is shown in Figure 1. The system includes the reactivity anomaly detection subsystem and the boiling detection subsystem.

Reactivity anomaly detection subsystem

The reactivity anomaly detection subsystem aims at detecting reactivity effects due to abnormal occurrences in the reactor core and is designed by applying the reactivity balance principle.

The reactivity balance calculation is performed based on the physical model of the reactor core which is assumed to be operated in normal state. The physical model includes the neutron kinetics and the temperature dynamics based on which the feedback reactivity effects are calculated.

The residual reactivity component is defined as the difference between the net reactivity and the sum of the feedback reactivity, control rod reactivity and burnup reactivity components. Since the model does not include explicitly any reactivity effect due to abnormal occurrence in the reactor core, the abnormal reactivity effect such as the void reactivity effect due to coolant boiling will be included in the residual reactivity component. The error arising from inaccurate physical model of the core dynamics as well as from inaccurate signal measurement will also be included in the residual reactivity component.

The input signals to this subsystem are the neutron flux, the inlet and outlet coolant temperatures, coolant flowrate, control rod position and other information which is necessary to adjust the parameters in the model. Because the measured signals are more or less corrupted by the measurement noise, a type of optimal estimation technique, more specifically the extended Kalman-Bucy filtering technique, is applied in order to improve the accuracy of estimating the reactivity components. The estimator of net reactivity has already been developed and tested using the experimental data. It has been shown that the reactivity estimator based on the optimal estimation technique has better accuracy than the conventional reactivity meter based on the inverse kinetics method.

Boiling detection subsystem

The role of boiling detection subsystem is to detect coolant boiling as early as possible by performing noise analysis of the related signals such as the neutron flux, the acoustic signals, etc. In Figure 1, lower part of the diagram corresponds to the boiling detection subsystem to be developed. The main body of this subsystem is the noise analysis block while in the reactivity anomaly detection subsystem it is the noise filtering block (i.e. Kalman-Bucy filter).

The measured signals are fed to the preprocessing block and then to the analysis block where the preprocessed signals are analysed by a set of standard analysis methods such as the correlation, the spectral, the coherence analyses, etc. The results of the analysis block are then fed to the display block and to diagnosis block. In the diagnosis block is made further analysis of the outputs from the analysis block in order to make diagnostic decision.

The values and functions to be computed in the analysis block include:

1) mean square values
2) auto- and crosscorrelation functions
3) auto- and cross-power spectral density functions
4) coherence functions
5) parameters in auto-regressive models
6) parameters in pattern recognition models

The pattern recognition methods will be applied in the analysis block as well as in the diagnosis block.

Other subsystems

Other anomaly detection subsystems such as abnormal vibration detection subsystem will also be studied in order to develop the identification method of the causes of reactivity anomaly. Some experiences have been aquired in diagnosing reactivity anomalies in thermal reactors and will be applied effectively to fast reactors.

3. Hybrid Computer Simulation

Since the objective of this simulation study is not to study detailed physical aspect of the boiling process itself but to investigate efficient method of signal processing suitable for detecting coolant boiling under a variety of signal to noise conditions, the simulation models used here are rather rough and qualitative than accurate and quantitative.

In Figure 2 is shown the functional block diagram of the hybrid computer simulation for boiling detection study. It consists of the void simulation, the neutronic signal simulation, the acoustic signal simulation, the noise generation and the signal processing blocks.

Void simulation

The basic signal to be generated in the present simulation is the void signal which simulate the patterns in time of the growth and collapse of the bubbles formed due to coolant boiling. For the simulation of the time variation of void volume, a multivariable function generator is used. The void patterns are chosen taking into consideration the experimentally observed bubble formation patterns.

The function generator is driven by a random signal in order to simulate the randomness in the time of bubble formation. The signal thus generated is then multiplied also by a random signal in order to simulate the randomness in the size of bubbles formed. Although it is assumed for the sake of simplicity in the present simulation that a single bubble is formed at a time, it is also easy to simulate the situation where several bubbles are randomly formed at a time by using several independent function generators..

Neutronic signal simulation

A point reactor kinetics model with six delayed neutron groups is used for the simulation of neutronic signal generation. A linearized reactor model is used because small amplitude of signal is concerned in the present study and the prompt jump approximation is applied in the case of fast reactor model.

At the input of the reactor simulator is applied the reactivity signal which is the sum of the void reactivity signal and the noise signal simulating random reactivity disturbances due to other causes such as fluctuation of coolant flowrate, for instance.

At the output of the reactor simulator is also applied another noise signal in order to simulate the measurement noise. The resultant signal is then fed to the signal processing block.

Acoustic signal simulation

The acoustic signal is generated based on the void signal. In the present simulation, the acoustic signal is generated by taking time derivative of the void signal according to the model developed by Wright. More realistic simulation of acoustic signal would be combined use of the model generated signal and the experimentally recorded boiling acoustic signals.

At the output of the acoustic signal simulator is applied random signals which simulate the background noise and the measurement noise. The resultant signal is then fed to the signal processing block.

Noise generation

In the present study, simulation of noise signals is important. In order to provide several independent noise signal sources and also to keep repeatability of simulation, a multichannel analog magnetic data recorder is used as the noise generator. On the magnetic tape are recorded various type of noise signals (several statistically uncorrelated white noise signals, pulsive noise signals and experimentally recorded acoustic signals).

The white noise signals are used directly or after passing appropriate filters according to the noise conditions required for simulation.

Signal processing

The main body of the signal processing block is the digital part of the hybrid computer for which program package of reactivity estimator and statistical signal analysis has been developed. In addition to the program package implemented on the hybrid computer, a commercially available signal analyzer is also used.

Results of simulation

Series of computer simulation for a variety of signal and noise conditions are being made by applying correlation and spectral analyses in order to study the methods of signal processing. The following general remarks can be made from the preliminary results so far obtained.

1) For the recognition of boiling by visual monitoring of the displayed functions, the spectral density functions are easier for recognition than the correlation function in most of cases studied, especially when the measurement noise is large.

2) In the case of relatively low signal-to-noise ratio where the power spectral density functions of both neutronic and acoustic signals poorly indicate the occurrence of boiling, the cross-power spectral density function and the coherence function are usually more effective for identifying it.

3) For a variety of noise characteristics, especially in the case of low signal-to-noise ratio, the coherence function is usually a better indicator of boiling provided that the void reactivity coefficient is not practically zero.

4) Capability of boiling detection can be improved to a certain extent by preprocessing of the measured signals before processing them by standard methods of analysis. For example, the detection capability is improved by applying simple nonlinear preprocessing such as squaring and level discrimination to the measured signals. However, the method of preprocessing optimal for particular application will depend much upon the signal and noise characteristics in the specific plant.

Figure 3 shows an example of case study where the mean repetition period of bubble formation is chosen as 150 msec with random variation of 30% around it. The signal-to-noise ratios in peak-to-peak value are about 0.7 for the neutron flux and about 1.5 for the acoustic signal. The peaks in the spectral density and coherence functions at about 7 Hz correspond to the mean repetition frequency of bubble formation. These peaks becomes clearer by making level discrimination as shown in Figure 4, which leads to improved detection capability. Similar results can be obtained by squaring the measured signals.

4. Concluding Remarks

The basic problems of signal processing for boiling detection are being studied by use of a hybrid computer which provides convenient and flexible means of simulating multivariate random processes such as the boiling related noise process.

It is necessary, however, to check the validity of computer simulation by making some experiments if simplified models are used for simulation. Especially, this is true since the boiling acoustic signals measured in actual reactors cannot be modelled accurately because of the complexity of sound wave propagation and the background noise which are much dependent on the specific structure of the reactor.

Since no in-pile sodium boiling experiment is planned in the Mark-I core of the experimental fast reactor JOYO, it is planned to make a boiling detection experiment using a LWR-type zero power reactor in order to compare the experimental results with those of the corresponding computer simulation. Some prelimainary experiments on boiling acoustics have already been started in order to design an appropriate device for the in-pile experiment.

References

1) J. Shimazaki et al.: "Development of the reactivity anomaly detection system for fast reactor" (in Japanese), JAERI-memo 8871 (1980)

2) J. Shimazaki et al.: "Development of the reactivity anomaly detection system for fast reactor (II)" (in Japanese), JAERI-memo 9406 (1980)

3) S. A. Wright: "Sodium boiling detection in LMFBRs by acoustic-neutronic cross-correlation", TID-97579 (1975)

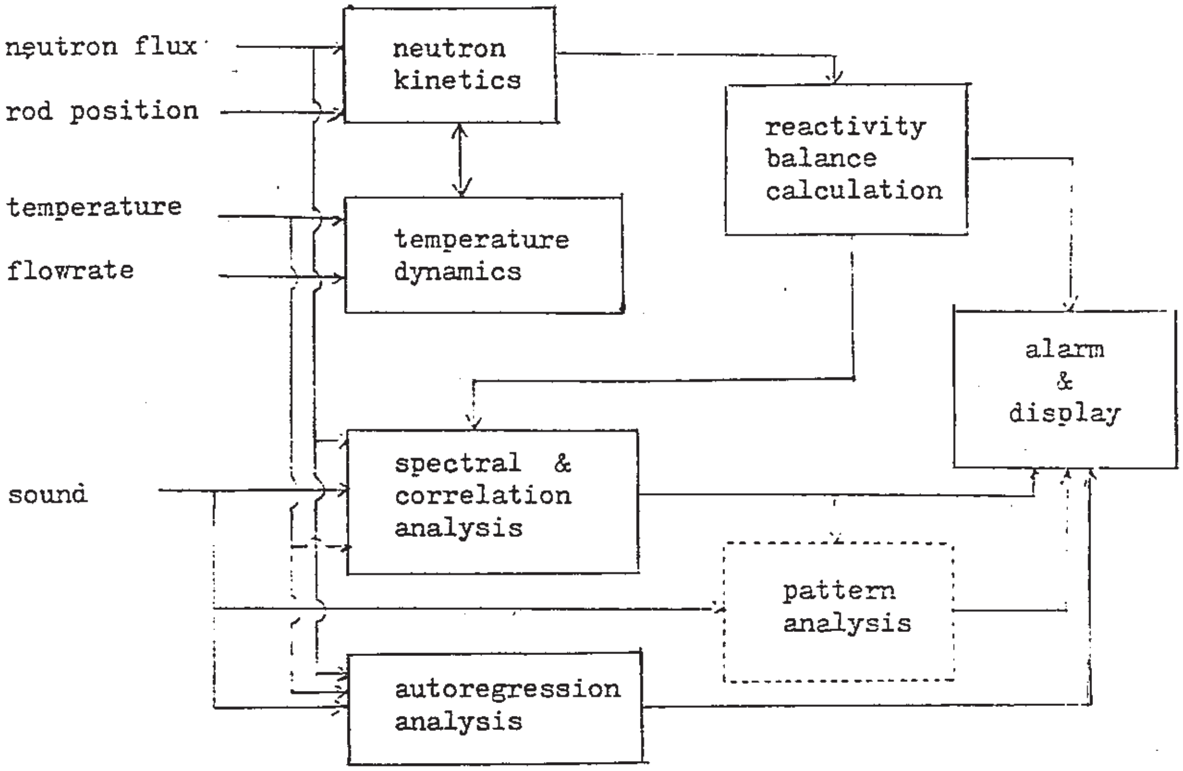


Figure 1. Block diagram of core anomaly detection system

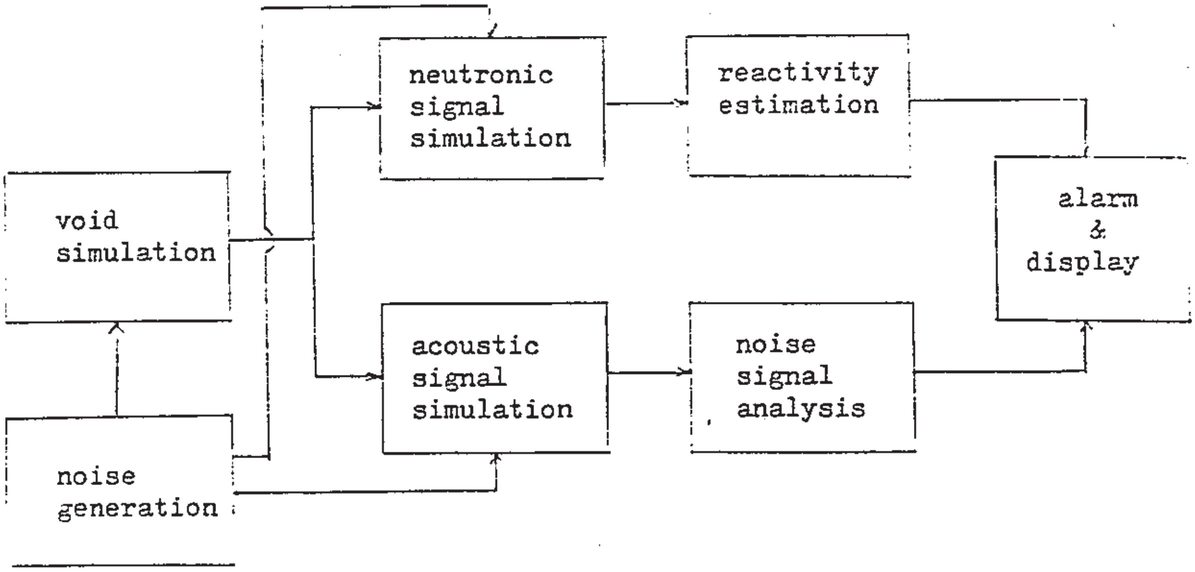
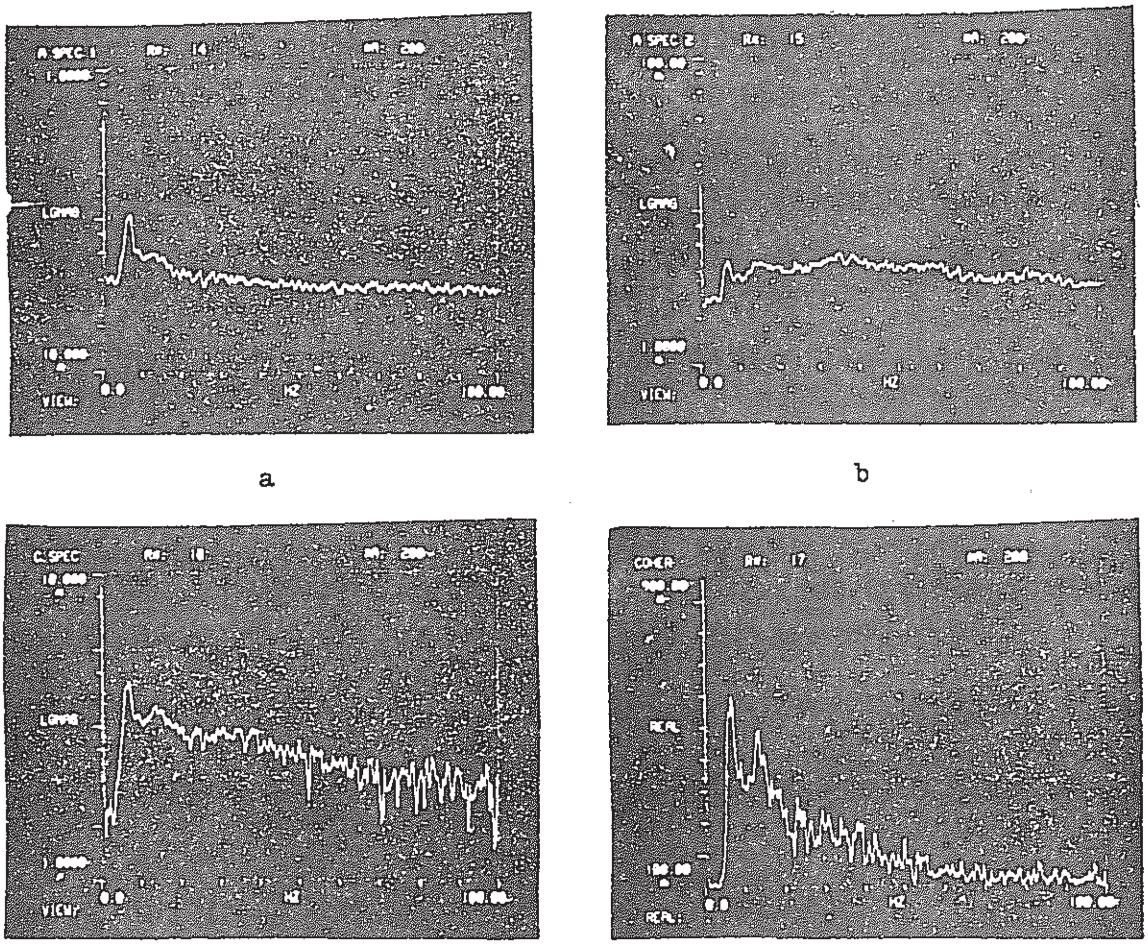


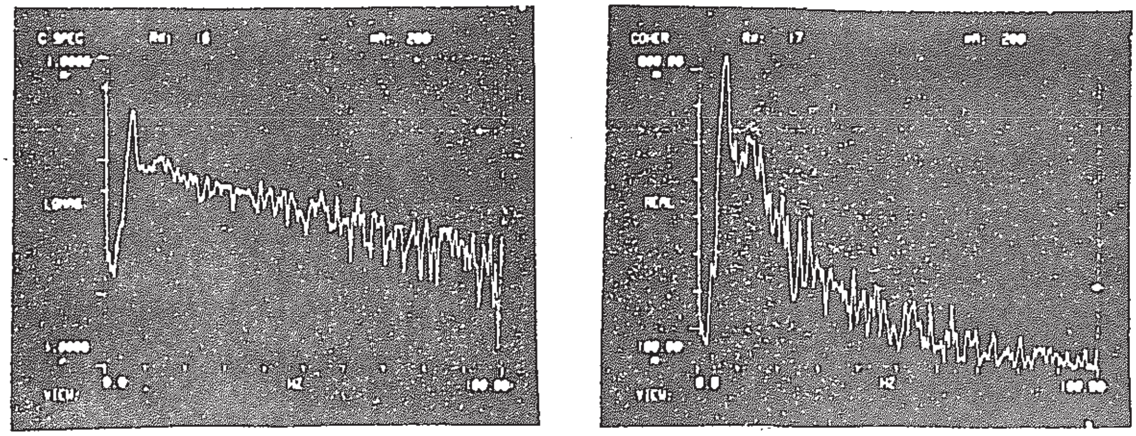
Figure 2. Functional block diagram of computer simulation



a b

c d

Figure 3. An example of simulation case study
a: auto PSD of neutron signal, b: auto PSD of acoustic signal
c: cross PSD , d: coherence function



a b

Figure 4. An example of case study with preprocessing of acoustic signal
a: cross PSD , b: coherence function